AN ANALYSIS OF STABILITY PROPERTIES IN OPERATING AND SUPPORT COSTS FOR AIR FORCE AIRCRAFT

THESIS

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Abstract

Accurately predicting Operating and Support (O&S) costs is vital in the current climate of budgetary constraints. However, there is an overall lack of research in the realm of O&S which hinders cost estimator's abilities to provide accurate sustainment estimates. This research determines when Air Force Aircraft O&S costs stabilize and to what degree. Stability is examined in three areas: total O&S costs, the six O&S cost element structures, and aircraft type. Stability results vary by category but generally is found to occur 80% of the time at approximately five years from Initial Operating Capability (IOC). The second portion of this research employs a multiple regression model to predict median O&S costs per total active aircraft in the inventory (CPTAI). All O&S costs and variables for regression derived from the literature are collected using the Air Force Total Ownership Cost (AFTOC) database. The model explains 87.24% of the variance in the data set when predicting median O&S CPTAI. Results from this research provide insight to cost estimators on when to start using actual O&S costs as a baseline for estimates in lieu of analogous programs and provides a new parametric O&S estimating tool designed as a cross-check to current estimating methodologies.

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Dedication

This Thesis is dedicated to my family and friends who have supported me throughout my educational career. I could not have made it this far without all of your help.

Acknowledgments

I would like to express my sincere appreciation to my research advisor, Lt Col (Ret.) Daniel Ritschel, for his guidance and support throughout the course of this thesis effort. I appreciate the structure he provided while also the freedom that allowed me to dive into the questions and solutions that I felt important. I would also like to thank Dr. Edward White for opening my eyes to the wonderful world of statistics and the sheer knowledge he brought to the table in this research. Finally, I would like to thank my sponsor, Captain Gregory Brown, from Air Force Life Cycle Management Center for taking an active role in the research and providing the insights needed to make this research useable to the cost estimation community.

Scott C. Hewitson

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I. Introduction

Chapter Overview

Every acquisition program funded by the Department of Defense (DoD) must consider the costs of sustaining and maintaining the system past its acquisition phase. Traditionally, the costs of the Operating and Support (O&S) phase has been deemphasized with more attention on estimates for the acquisition phase (Ryan, Jacques, Ritschel, and Schubert, 2013). Furthermore, DoD research from 1945-2008 has included dozens of studies and commissions on the accuracy of acquisition cost estimates with no published work on O&S estimates (Ryan et al., 2013) This lack of research in O&S costs is puzzling given that O&S is typically the largest component of a platform's life-cycle cost. While conventional wisdom has typically considered O&S costs to be 70% of a system's total life-cycle costs, more recent research has found a mean of 50-55% with large deviations depending on platform type (Jones, White, Ryan, and Ritschel, 2014). More specifically for aircraft, Jones et al. (2014) found fighters had a mean of 52.99% and cargo/tanker had a mean of 65.15%. While these numbers are lower than what has been traditionally portrayed as the standard, they are still more than half of total life-cycle costs. In addition to being a large portion of the life-cycle, O&S costs have risen on an annual basis and therefore, require more scrutiny in the budgetary process.

O&S costs are hard to predict early in a program's life-cycle because the aircraft is often new and actual operational data may not exist. As a result, potential unexpected problems may occur that results in additional O&S costs. On the other hand, new aircraft may not experience as many problems as seasoned aircraft and significant costs in maintenance may not materialize early. These reasons make early O&S costs difficult to estimate and may result in inaccurate budgets. DoD programs are examined closely in today's environment of budgetary constraints and an accurate estimate provides senior leaders the data to make proper decisions. Large swings in year-to-year O&S costs may cause budgetary realignment problems such as under-funding other programs or under-execution of funds. Thus, research into understanding stability properties in O&S costs is needed. Knowing when stability occurs in a program is important for analysts when they create long term O&S estimates because stabilized costs reduce uncertainty in the estimate. Also, if it is determined that a program is stable then analysts can utilize actual O&S data related to the platform's performance for the out-year estimates instead of relying on analogies, factors, or other cost estimating techniques. Previous research by Jones et al. (2014) assumed that a program's O&S costs would be considered "stable" when at least 10% of the planned procured quantity were produced. The 10% inclusion criterion was employed to simplify the data set; however, it was not tested with statistical evidence and may not be an appropriate metric.

Outside major upgrades or mission changes, an aircraft's O&S costs should theoretically stabilize. However, a determination of when or what characteristics lead to stability have not yet been explored. Despite this research gap, reporting policies for O&S costs have been levied upon Air Force program offices. Current reporting under Air Force Material Command's (AFMC) Weapon System Enterprise Review (WSER) requires an acquisition program to report O&S costs and how they relate to previous years. According to WSER, a program is considered "green" when the current O&S cost is less than 15% of the 2-year historical average cost, "yellow" when the current O&S

cost is within 15% under or over the 2-year average cost, and “red” when current O&S costs are over 15% of the 2-year average cost (Air Force Material Command, 2016). These ranges may not be a good indicator of program success as early O&S costs vary for a multitude of reasons.

Purpose

The purpose of this thesis is to determine when O&S costs stabilize for Air Force aircraft to add accuracy to cost estimates. This research is scoped to the all Air Force aircraft in the inventory. Improving the accuracy of O&S estimates will aid decision makers when deciding whether to start a new program or continue to fund O&S for an established program. Furthermore, the research will determine a new data driven threshold for reporting or validate whether the 15% currently used in WSER has merit. Finally, a multiple regression model is made to determine total O&S costs per aircraft as a top level cross check.

Research Questions

#1: Using the Weapon System Enterprise Review (WSER) 15% threshold for reporting as a baseline, what is the more accurate, data driven threshold for stability? Analysis of WSER reporting guidelines and prior year O&S costs helps determine a data-driven threshold for when acquisition programs should be reporting O&S expenditure issues.

#2: When can O&S costs of a program be considered stable? The database Air Force Total Ownership Cost (AFTOC) is utilized to pull actual O&S costs for each aircraft to determine when they can be considered stable determined by years from Initial

Operational Capability (IOC). Air Force programs are examined but the method is replicable with other service's O&S costs.

#3: How do stability characteristics vary by platform type? AFTOC data is grouped by aircraft platform type and then analyzed in these separate pairings.

#4: Using multiple regression, how accurately can we predict O&S costs for a given year using explanatory variables? Programmatic data from AFTOC and other sources are used to predict the O&S costs for given year. Relevant programmatic data are total aircraft in the inventory (TAI), average age of fleet, flight hours, among others.

Methodology

Research questions one, two, and three require AFTOC O&S cost data for analysis. Data needs to be standardized to ensure comparisons are equivalent. The research standardizes years of cost data by the years from IOC. Additional standardizations include cost per flying hour (CPFH) and cost per total aircraft (CPTAI) for an accurate comparison from year to year. Once the data is standardized, calculations for the percent change from year to year can be determined. With percent changes calculated, we can determine when programs stabilize and how stable they are to a certain percentage bound.

Regression analysis also requires the use of AFTOC cost data in addition to programmatic data. The model building process is iterative and requires passing key diagnostics. Once all diagnostics are passed it can then be validated with a separate validation pool.

Scope and Limitations

The scope of this research is to analyze Air Force aircraft programs. Data gathered in AFTOC is from 1996-2016. 2017 is excluded from this analysis to ensure only full year expenditures are being examined. Aircraft are split into eight mission categories provided by AFTOC: Bomber, Fighter/Attack, Helicopters, Reconnaissance, Special Duty, Training, Transport/Tanker, and Unmanned Aerial Vehicles (UAV). While the research is only focused on Air Force Aircraft, the relationships found may be applicable to other types of programs or services. AFTOC is an authoritative resource of actual O&S costs incurred by a program, but it is important to note that large databases may have inconsistencies or errors in data. While there are potential issues, AFTOC is a database maintained by contractors and is periodically updated when additional information is received. Another limitation of this research is that some programs may not have reached stabilized O&S costs due the infancy of the program.

Chapter Summary

The following chapter contains a literature review of the previous research completed on O&S cost estimation as well as DoD guidance for O&S estimates. In addition, the chapter includes information on the WSER and its application to stability properties. Following the literature review is Chapter Three that outlines the methodologies used to answer the research questions. Chapter Four outlines the stability properties of programs as well as the results of the multiple regression to predict O&S costs. The closing chapter discusses the implications of the research for decision makers and potential areas for follow-on research.

II. Literature Review

Chapter Overview

This chapter discusses the importance of Operating and Support (O&S) costs in the Department of Defense (DoD). Federal regulations and reports from independent government agencies conveying the significance of these costs are included. Furthermore, the guides for federal and DoD specific O&S cost estimates provide the reader with an understanding of how these costs are calculated and which components are included. Then provided is a review of the limited O&S cost estimate research to date, further explaining why government agencies do not have an in-depth understanding on how to estimate these costs. The driving force for analyzing stability properties in this research is the Weapon System Enterprise Review (WSER). The most recent WSER business rules for O&S cost reporting are detailed. Definitions of stability in O&S cost estimates are not clearly defined in previous research, therefore how this could be helpful in estimating programs more accurately is investigated. Finally, analysis from Earned Value Management (EVM) provides an insight on how stability properties may be calculated for O&S cost estimates.

Emphasis on Operation and Support Costs

DoD programs typically have four main phases in the life cycle of a system: Research & Development (R&D), Procurement (Investment), O&S, and Disposal. However, the O&S and Disposal phases are usually combined for simplicity. Of these phases, the largest cost by percentage of the total life-cycle has widely been accepted as O&S (Jones, White, Ryan, & Ritschel, 2014). This widely accepted “golden rule” is that

70% of life cycle costs will be attributed to sustainment (O&S) costs. Figure 1 illustrates the total life cycle costs and is adapted from the Office of the Secretary of Defense Cost Assessment & Program Evaluation (OSD CAPE).

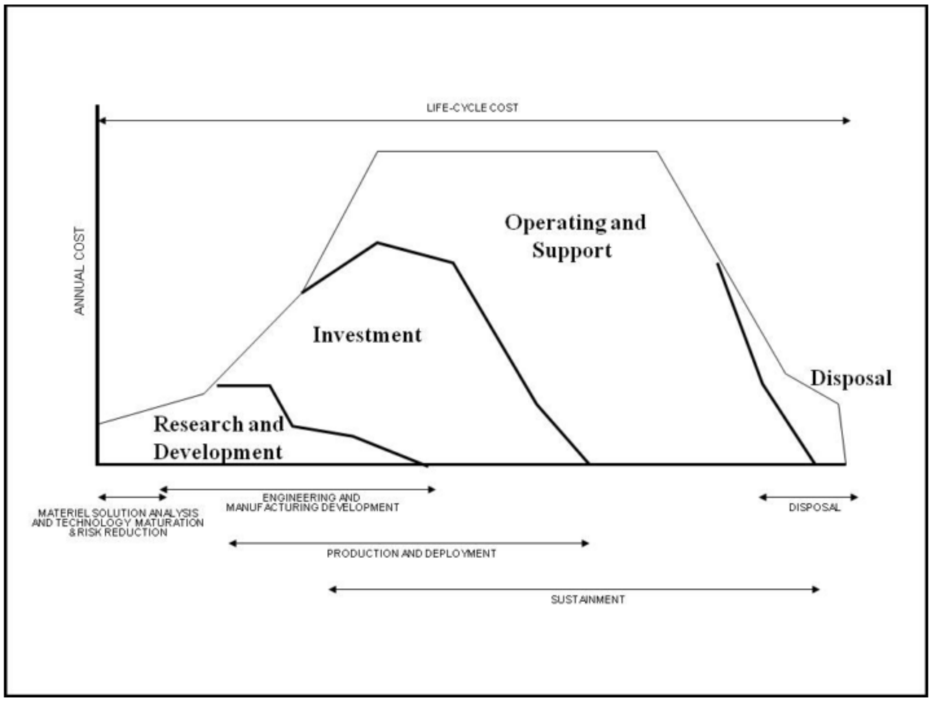


Figure 1. Illustrative System Life Cycle (OSD CAPE, 2014)

In the past, program offices focused less on O&S costs compared to the acquisition costs, comprised of the R&D and Procurement phases. Acquisition programs span from as a little as one year for a small weapon system to 15-20 years for entirely new aircraft. Given the duration of the acquisition cycle, it is easy for program managers (PMs) and other functional support staff to be extensively focused on near term goals and affordability. PMs work on a program for a short number of years and then move to another program. The focus is on near term program success and to ensure execution of current year funding, especially with the uncertainty of future budgets. No matter how hard a PM tries, it is impossible to predict problems and costs associated with sustainment that may occur decades into the future. Understandably, there is a tradeoff between focusing on present affordability and driving sustainability of costs down for future managers of a program.

The focus on affordable R&D and Procurement costs in programs over O&S costs is also reflected in academic research in the discipline. “Meanwhile, the O&S sustainability considerations have been perennially neglected or subordinated to acquisition requirements or program survival” (Ryan, Jacques, Ritschel, & Schubert, 2013). According to Ryan’s research, from 1945 to 2008, there were over 130 studies focused on the acquisition of DoD systems, many of which involved the accuracy of the cost estimates while not a single published study pertained to the accuracy of O&S cost estimates (Ryan et. al., 2013). Without academic research and emphasis on the importance of O&S, the techniques used to estimate these costs have improved little over time.

However, more attention has been given to the O&S portion of the DoD budget in recent years. Between political pressures and the ever-rising national debt, congress created the Weapon Systems Acquisition Reform Act (WSARA) in 2009. WSARA dictates that “Not later than one year after the date of the enactment of this Act, the Comptroller General of the United States shall submit to the congressional defense committees a report on growth in operating and support costs for major weapon systems” (Public Law, 2009)

In addition to reporting cost growth, the act also dictates that if possible, service and repair contracts for weapon systems must solicit competition to drive costs down. This would help alleviate the budgetary pressures large defense contractors put on the

U.S. government by charging any price for sole source repair or maintenance contracts. Finally, the Office of Secretary of Defense Cost Assessment and Program Evaluation (OSD CAPE) was created as result of WSARA to help carry out the act (Public Law, 2009). WSARA explicitly emphasizes O&S focus in a handful of facets and the latent function is that the emphasis has spilled over into other areas within the DoD.

Two months before WSARA became law, the United States Government Accountability Office (GAO) published its cost estimation guide to “establish a consistent methodology that is based on best practices and that can be used across the federal government for developing, managing, and evaluating capital program cost estimates” (Government Accountability Office, 2009). The guide is a top-level approach for all government programs, not just the DoD. According to the GAO, “A life-cycle cost estimate provides an exhaustive and structured accounting of all resources and associated cost elements required to develop, produce, deploy, and sustain a particular program’s life” (Government Accountability Office, 2009). Given financial issues in the country at the time, government agencies began to focus on better spending practices moving forward.

In 2010, just one year after WSARA, the GAO produced a report that concluded the DoD does not effectively record and track O&S cost estimates throughout the life-cycle of a weapon system and needs to retain documentation to do so (Government Accountability Office, 2010). For the programs GAO investigated, information for estimates was missing and in some cases the cost estimates were never completed. At the time of the report, DoD services failed to produce life-cycle O&S cost estimates for five of the seven aviation systems reviewed (Government Accountability Office, 2010). The lack of past data and less emphasis on O&S are likely reasons why the DoD was unable to produce the deliverables for GAO.

In 2012, yet another report from the GAO was published, titled *Improvements Needed to Enhance Oversight of Estimated Long-term Costs for Operating and Supporting Major Weapon Systems* (Government Accountability Office, 2012). The report concluded that the DoD does not do a sufficient job in reporting O&S costs in the uniform fashion it is meant to. Program offices are supposed to report O&S cost data via Selected Acquisition Reports (SARs). However, a large portion of programs were unable to document some or all of the following: "(1) the explanatory information they included with the cost estimates; (2) the source of the cost estimates they cited as the basis for the reported costs; (3) the unit of measure they used to portray average costs; (4) the frequency with which they updated reported costs; and (5) the reporting of costs for an antecedent system being replaced by the new weapon system" (GAO, 2012). This published report is further evidence that at the time the DoD was still having O&S cost and reporting issues needing to be resolved.

Cost Estimation Guides

Prior to WSARA, the Office of The Secretary of Defense Cost Analysis Improvement Group (OSD CAIG) was the DoD's source for O&S cost estimation guidelines. Original guidance came in 1992 and was improved upon in 2007. The creation of OSD CAPE resulted in a new guide in 2014 for DoD components to develop estimates of system operating and support costs (Office of the Secretary of Defense; Cost Assessment and Program Evaluation, 2014). The 100+ page guide is intended to be a handbook for cost analysts and ensures all aspects of O&S costs are captured in the estimate. Though OSD CAIG had a similar breakdown of O&S costs, OSD CAPE's newest cost element structure is shown in Figure 2. Operation and support of weapon systems may seem simple but the cost element structure provides an outline to the complex list of costs that can make up an estimate.

Second-Level/Third-Level
O&S Cost Estimating Structure

1. Unit-Level Manpower
   - 1.1 Operations
   - 1.2 Unit-Level Maintenance
   - 1.3 Other Unit-Level
2. Unit Operations
   - 2.1 Operating Material
   - 2.2 Support Services
   - 2.3 Temporary Duty
   - 2.4 Transportation
3. Maintenance
   - 3.1 Consumable Materials and Repair Parts
   - 3.2 Depot Level Reparables
   - 3.3 Intermediate Maintenance (External to Unit-Level)
   - 3.4 Depot Maintenance
   - 3.5 Other Maintenance
4. Sustaining Support
   - 4.1 System Specific Training
   - 4.2 Support Equipment Replacement and Repair
   - 4.3 Sustaining/Systems Engineering
   - 4.4 Program Management
   - 4.5 Information Systems
   - 4.6 Data and Technical Publications
   - 4.7 Simulator Operations and Repair
   - 4.8 Other Sustaining Support
5. Continuing System Improvements
   - 5.1 Hardware Modifications
   - 5.2 Software Maintenance
6. Indirect Support
   - 6.1 Installation Support
   - 6.2 Personnel Support
     - 6.2.1 Personnel Administration
     - 6.2.2 Personnel Benefits
     - 6.2.3 Medical Support
   - 6.3 General Training and Education
     - 6.3.1 Recruit & Initial Officer Training
     - 6.3.2 General Skill Training
     - 6.3.3 Professional Military Education

Figure 2. OSD CAPE O&S Cost Estimating Categories (OSD CAPE, 2014)

The Air Force Cost Analysis Agency (AFCAA) created the Air Force Cost Analysis Handbook (AFCAH) in 2008. The handbook details how cost estimators should create estimates for both acquisition and sustainment phases. However, the most recent version came out before WSARA and the newfound emphasis on O&S costs. While the guide extensively details cost estimation techniques for the acquisition phase it lacks O&S techniques. For a general idea, there are 17 chapters in the AFCAH and only one chapter details O&S cost estimation (Air Force Cost Analysis Agency, 2008). The handbook also fails to consider stability when creating O&S cost estimates.

One area where AFCAH acknowledges instability of O&S costs is with Interim Contractor Support (ICS). After the Procurement phase of a program the system must be sustained. For this temporary period, the logistics and maintenance support are completed by the contractor. "[ICS] may be used when there is uncertainty in the type and level of support required due to system, equipment, or end-item design instability that may put the system's logistics support elements at risk." (AFCAA, 2008). While this allows programs to hedge against risk for one to three years after production, this doesn't help cost estimators once support from the contractor has ended. ICS is discussed in the O&S chapter of the AFCAH however it is budgeted for with procurement appropriations and is considered while doing the acquisition cost estimate.

AFCAH acknowledges that O&S estimates are complex and recommends similar cost estimation tools that are used in acquisition estimates such as parametric and simulation tools. One simulation tool example is the estimation of steady-state depot repair costs for depot level reparable (AFCAA, 2008.) The tool might be helpful but steady-state (stability) is assumed and not guaranteed. Without stability, the tools presented in this chapter may not have the same validity as when they are used in estimating acquisition costs.

Research on Operation and Support Costs (Pre-WSARA)

While the recent emphasis on O&S costs has influenced academic research, there are published works that considered the effects of these rising costs prior to WSARA. The research reviewed in this chapter that came before WSARA speak to the cost effects of aging aircraft and the "death spiral" associated with these costs. In Dixon's dissertation, he explains that the spending “death spiral” is a cycle in which older equipment require more funds to maintain, which, in turn, decreases the funds available for new weapon systems (Dixon, 2005).

The Congressional Budget Office (CBO) researched the effects of aging on O&S costs for military equipment. CBO’s main purpose in their report was to answer two questions: 1) Do aging equipment and the associated costs of operating and maintaining it explain trends in total spending on O&M? 2) What can be learned from existing studies and data about the relationship between the age of equipment and the costs of operating and maintaining that equipment? (Congressional Budget Office, 2001). Total Operation and Maintenance (O&M) is comprised of other components in addition to spending on equipment. Other categories include but are not limited to: personnel, base maintenance, environmental factors, base operating support, and communications. For further clarity, O&M spending on equipment is considered O&S costs while the other components plus O&S comprise total O&M. According to CBO, O&S costs only comprised around 20% of the total O&M budget at the time of the study. The CBO study found that aging aircraft may be causing increases in O&S costs but there is not sufficient evidence to claim that it drives the total O&M budget up.

The second CBO research question is more general and aims to learn from previous studies. In its report, the CBO analyzed prior research that used data to derive relationships between aging aircraft and maintenance costs. Included in this analysis was both individual aircraft studies and pooled aircraft studies. Individual studies refer to studies that analyzed one aircraft at a time while pooled studies took a top-level approach and aggregated data of multiple aircraft. One of the significant pooled studies included was from the RAND corporation in 1990 (Hildebrandt & Sze, 1990). CBO replicated the process with available Air Force Total Ownership Costs (AFTOC) data. This is Air Force O&S data from a variety of aircraft platforms. Using data from 17 active aircraft from 1996-1999, they used the 68 observations to make a multiple regression tool to predict O&S costs. The parameters used were:

$$ln(COST) = \alpha + \beta_1 * AGE + \beta_2 * ln(TEMPO) + \beta_3 * ln(PAUC) + \beta_i * Ydummies + e$$

Where:

COST	=	operating costs/inventory
α	=	intercept term
AGE	=	average annual age/100
TEMPO	=	annual flying hours/inventory
PAUC	=	procurement average unit cost
Ydummies	=	dummy variables for years

β values in the equation above are the coefficients for each term. CBO's replication of the 1990 Rand equation with updated data resulted in an $R^2 = 0.71$. In addition to the original model, CBO added to the model by including dummy variables for aircraft type. The actual data on the second model was not given in the report but it did say with 99 percent confidence that the second model was more appropriate (Congressional Budget Office, 2001). The RAND model does not include stability in its variables but can provide a top-level cross-check for analysts completing cost estimates.

In 2005, Dixon investigated the effects of aging aircraft on costs but focused on the commercial sector rather than military. In his work, Dixon states the United States military can use insights gained from the cost of aging commercial aircraft fleets for long-term military aircraft maintenance estimates (Dixon, 2005). He found that the total maintenance costs increase as the average fleet age increases. However, this increase is in a decreasing fashion. Prior to Dixon's investigation, consensus was that maintenance costs continue to increase due to aging fleets. The traditional thought would make the curve of these costs have a cubic shape that has an increase in the Newness stage, a leveling off in the Mature stage, and an increase in the Aging stage. Dixon designed his methodology to recreate the accepted cubic curve and use the three categories that Boeing used in its model to demonstrates costs of aging fleets. Figure 3 illustrates how the costs of aircraft per flight hour are influenced by average fleet age. It is important to note that the cost curve does not follow a cubic shape but rather a logarithmic. Also, included are the three categories of aircraft age originally presented by Boeing.

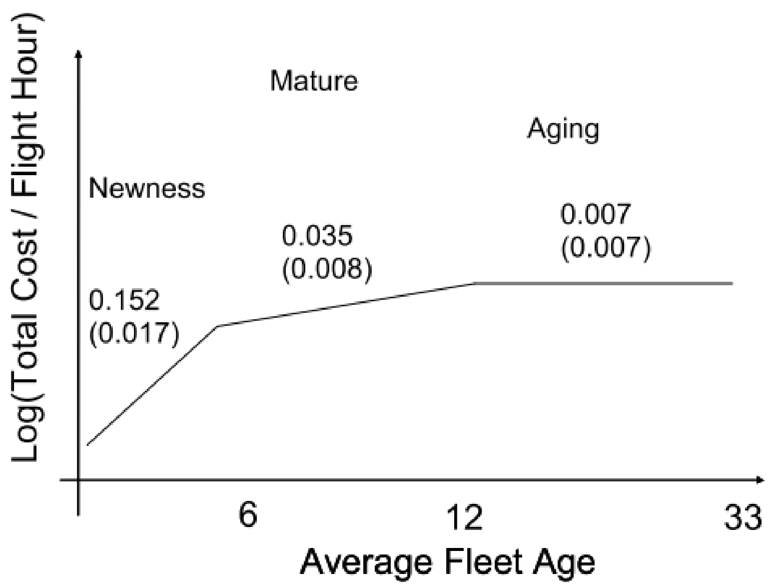


Figure 3. Estimated Costs with Respect to Fleet Age (Dixon, 2005)

The research examined passenger airline aircraft which have a significantly different flight mission compared to military aircraft. Due to this difference, the applicability may be limited to certain types of aircraft or missions. Aircraft such as tankers and cargo airlift are more analogous to commercial aircraft and may be able to use the results as support for repair or replace decisions faced by senior leaders.

Research on Operation and Support Costs (Post-WSARA)

Since the enactment of WSARA there has been a greater emphasis on O&S costs and research in the field. Stephen Harrison, an Australian that used open source U.S. cost data, tested the hypothesis that newer aircraft should have lower O&S costs but found that costs are rising year to year. "The comparison of the O&S costs of 21 platforms and their antecedent has shown that only seven of them are cheaper to operate" (Harrison, 2013). Improvements in technology would appear to drive maintenance costs down but the evidence demonstrates that it may be cheaper to continue maintaining an old aircraft than investing in a new aircraft for the same mission. In his research, he notes that the reason given for the increase in O&S costs for the F-35 to its antecedent is due to the vast jump in capability the new fighter has and must maintain.

In 2013 Ryan, Jacques, Ritschel, & Schubert found that "There tend to be large errors in DoD O&S cost estimates, and that the accuracy of the estimates improves little over time." They also note that from 1945 to 2008 there were over 130 studies dedicated to checking the accuracy of acquisition cost estimates and none focusing on O&S (Ryan et al., 2013). For such a large portion of the life cycle costs it would be logical to assume there would be more prior research in the field.

The widely accepted 70% ratio of O&S to life-cycle costs was further investigated in 2014. AFCAH and the GAO cost estimating guide both have fixed wing aircraft R&D costs at 20% of life cycle costs, procurement at 39%, and O&S at 41% (AFCAH, 2008. GAO, 2009.) These values are inconsistent with the 70/30 rule referenced in other DoD literature. The lack of data to back up the 70/30 rule drove Jones' research. "O&S costs vary by aircraft type and are a significant portion of costs but do not follow the traditional convention of being 70% of the life cycle" (Jones et al., 2014). Table 1 summarizes the ratios Jones found for O&S costs to total life cycle costs based on aircraft platform. Jones also investigated the ratios for ships, missiles, helicopters, electronic equipment, and tilt rotor aircraft however the scope of this research only includes fixed wing aircraft.

Harrison (2013) also pointed out that it is more relevant to examine the ratio percentage by group of common platform types. Highest deviators from the 70/30 rule in his research include submarines at 40/60 and weapons at 10/90. The deviations of O&S costs regardless of program type lend to the fact that they are difficult to accurately estimate (Harrison, 2013).

Table 1. Summary of O&S Cost Percentages by Platform (Jones 2014)

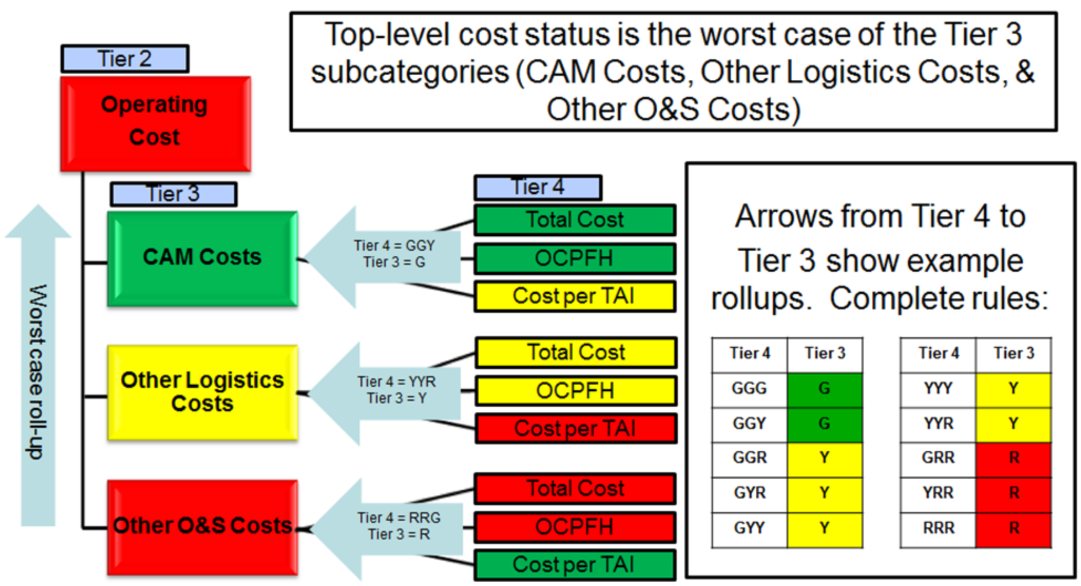
Aircraft Platform	Mean	Median	Standard Deviation
Fighter	52.99%	51.46%	15.65%
Cargo/Tanker	65.15%	61.73%	13.98%
Cargo/Tanker-No KC-135R	59.94%	59.55%	9.68%
Unmanned Aerial Vehicles (UAV)	71.56%	71.56%	9.39%

Weapon System Enterprise Review

In 2012, Air Force Material Command (AFMC) consolidated its 12 centers to the five-center construct present today (Air Force Public Affairs, 2013). The restructuring led to the development of Air Force Life Cycle Management Center (AFLCMC) which oversees many of the Air Force acquisition programs. One of LCMC's responsibilities is to execute the Weapon System Enterprise Review (WSER). According to the 2016 draft WSER business rules, "The WSER provides a comprehensive, integrated, timely, rhythmic review focused on present and future health of Air Force weapon systems and

AFMC materiel enterprise effectiveness in support of overall Integrated Life Cycle Management (ILCM)" (Air Force Material Command, 2016). Program managers must brief a program if it is deficient in one or more of the 12 metrics used to track the program's success. Examples of these metrics include aircraft availability, service life, modernization, and logistics health assessment.

One of the metrics is the operating costs of a weapon system, synonymous with O&S costs. If a program's current year O&S costs are greater than 15% of the previous two-year average cost then the program is considered red (deficient) and must be briefed with its "Issues", "Impacts", "Way-Ahead", and "Get Well Dates" (Air Force Material Command, 2016). The subcategories of the O&S costs reported during the WSER are illustrated in Figure 4.



Tier 4	Tier 3	Tier 4	Tier 3
GGG	G	YYY	Y
GGY	G	YYR	Y
GGR	Y	GRR	R
GYR	Y	YRR	R
GYY	Y	RRR	R

Figure 4. O&S Cost Categories from the WSER Business Rules

Tier 3 cost status (color) is determined by the sub-table on the right of the figure and tier 2 status is determined by the worst-case cost status from tier 3. Tier 2 is the top-level roll up costs of tier 3. The first category in tier 3 is Centralized Asset Management (CAM) costs. The CAM category is comprised of the Weapon System Sustainment (WSS) portfolio, Cost Per Flying Hour (CPFH) program, and may include other non-CAM costs such as U.S. Southern Command, Air Force Reserve, and Air National Guard. The second category in tier 3 is Other Logistics Costs. Examples of these are all logistics costs that are not captured in CAM such as unit level maintenance costs. The final category in tier 3 is Other O&S Costs. These include any O&S costs in the portfolio that are not related to logistics but rather the operations. Tier 4 costs are broken into three categories; total cost, operational cost per flying hour (OCPFH), and cost per total aircraft in the inventory (Cost per TAI).

Table 2 summarizes how costs are categorized in the WSER based on the CAIG cost element structure. It is important to note that the OSD CAPE O&S cost element structure from 2014 from figure 2 supersedes the CAIG cost element structures from 2007 but WSER uses CAIG elements to construct its tier 3 cost categories. Both cost element structures are similar with minimal differences.

Table 2. WSER Cost Category Alignment with CAIG Elements

	WSER Operating Cost Categories			
CAIG Elements	CAM Costs	Other Log Costs	Other O&S Costs	Indirect Costs
1.0 - Unit Personnel				
1.1 - Operations Personnel			X	
1.1.1 - Pilot			X	
1.1.2 - Aircrew			X	
1.1.3 - Crew Technician			X	
1.1.4 - Command & Control			X	
1.2 - Maintenance Personnel		X		
1.2.1 - Organizational		X		
1.2.2 - Intermediate		X		
1.2.3 - Ordnance		X		
1.2.4 - Other Maintenance		X		
1.3 - Other Direct Support Personnel			X	
1.3.1 - Unit Staff			X	
1.3.2 - Security			X	
1.3.4 - Other Support			X	
2.0 - Unit Operations				
2.1 - Operating Material			X	
2.1.1 - Energy (Fuel, POL, Electricity)			X	
2.1.1.1 - AV Fuel			X	
2.1.1.2 - POL			X	
2.1.1.3 - Electricity			X	
2.1.2 - Training Munitions & Expendable Stores			X	
2.1.2.1 - Ammunition			X	
2.1.2.2 - Bombs			X	
2.1.2.3 - Rockets			X	
2.1.2.4 - Training Missiles			X	
2.1.2.6 - Pyrotechnics			X	
2.1.3 - Other Operational Material			X	
2.2 - Support Services		X		
2.2.1 - Purchased Services		X		
2.2.2 - Transportation		X		
2.2.3 - Other		X		
2.3 - TDY		X		
3.0 - Maintenance				
3.1 - Organizational Maintenance & Support				
3.1.1 - Consumables		X		
3.1.2 - Repair Parts	X			
3.1.3 - Depot Level Repairables (DLR)				
3.1.3.1 - Flying DLR	X			
3.1.3.2 - Non-Flying DLR		X		
3.1.4.1 - Interim Contractor Support		X		
3.1.4.2 - Contractor Logistics Support	X			
3.1.4.3 - Other Contractor Support	X			
3.3 - Depot Maintenance - Overhaul/Rework	X			
3.3.1 - Aircraft Overhaul/Rework Depot Repair	X			
3.3.2 - Missile Overhaul/Rework Depot Repair	X			
3.3.3 - Engine Overhaul/Rework Depot Repair	X			
3.3.4 - Other Overhaul/Rework Depot Repair	X			
3.3.5 - Other Non-Overhaul Depot Repair	X			
4.0 - Sustaining Support				
4.1.1 - System Specific Operator Training	X			
4.1.2 - System Specific Non-Operator Training	X			
4.1.3 - Simulator Operations	X			
4.2 - Support Equipment Replacement		X		
4.3 - Operating Equipment Replacement		X		
4.4.1 - Sustaining Engineering	X			
4.4.2 - Program Management	X			
4.5 - Other Sustaining Support		X		
5.0 - Continuing System Improvements				
5.1 - Hardware Modifications				
5.2 - Software Modifications	X			
6.0 - Indirect Support				
6.1 - Installation Support				X
6.1.1 - Base Operating Support				X
6.1.2 - Real Property Maintenance				X
6.2 - Personnel Support				X
6.2.1 - Personnel Administration				X
6.2.3 - Medical Support				X
6.3 - General Training & Education				X

Stability in O&S Estimates

Stability is a term that has rarely been used in O&S cost estimation but is an important characteristic. According to Merriam-Webster, the definition of stable as an adjective, reads:

a: firmly established: fixed, steadfast stable opinions

b: not changing or fluctuating: unvarying in stable condition

c: permanent, enduring stable civilizations (Merriam-Webster, n.d.)

In the realm of O&S cost estimation, the closest definition of stability is costs that are not changing or fluctuating. Nonetheless, sustainment is an ever-changing and fluid component in the life cycle so a better definition of stability may be costs that are **minimally** changing or fluctuating. Programs that can be considered to have stable O&S costs provide the cost estimator with confidence and less uncertainty that the estimations are correct. Once the program has reached stability, cost estimators can utilize the actual previous year expenditures as a baseline for the estimate. This is a huge benefit that saves time and relinquishes doubt that others may have in the estimate. Accurate cost estimations lead to proper budgeting which leads to available funding and eventually program success. Cost analysts have research tools and methods at their disposal to properly estimate the acquisition phase but the lack of research in the O&S realm limits the tools for the sustainment phase.

The only research that explicitly considers stability in its methods is Jones et al., 2014. In their analysis of the ratio of O&S to acquisition costs they look at programs they have deemed stable. In the research, a stable program is one that has produced at least 10% of the planned procurement quantities to avoid any ramp up affects that could skew costs (Jones et. al). In addition, there is no research to back up the 15% cost metric stated in the WSER business rules. The 15% WSER metric was constructed by analysts at HQ AFMC/A9, but may not have been derived through data analysis. Given prior research on inaccuracy and difficulties in O&S cost estimates, this may not be a proper metric. Knowing when a program's O&S costs will stabilize provides another tool for analysts to properly estimate the costs. At the very least it will provide clarity to those in the WSER process who must report on cost overruns. Figure 5 depicts a notional program that demonstrates stability within a 15% bound from year 2000 to around 2016. Assuming the initial operational capability for this example started in 1996 the expected profile depicts a ramp-up of costs at the beginning, a period of stability within the 15% bounds, and escalating costs near the end of its 20-year useful life. While this is a textbook example, deviations in actual programs from the trend are expected.

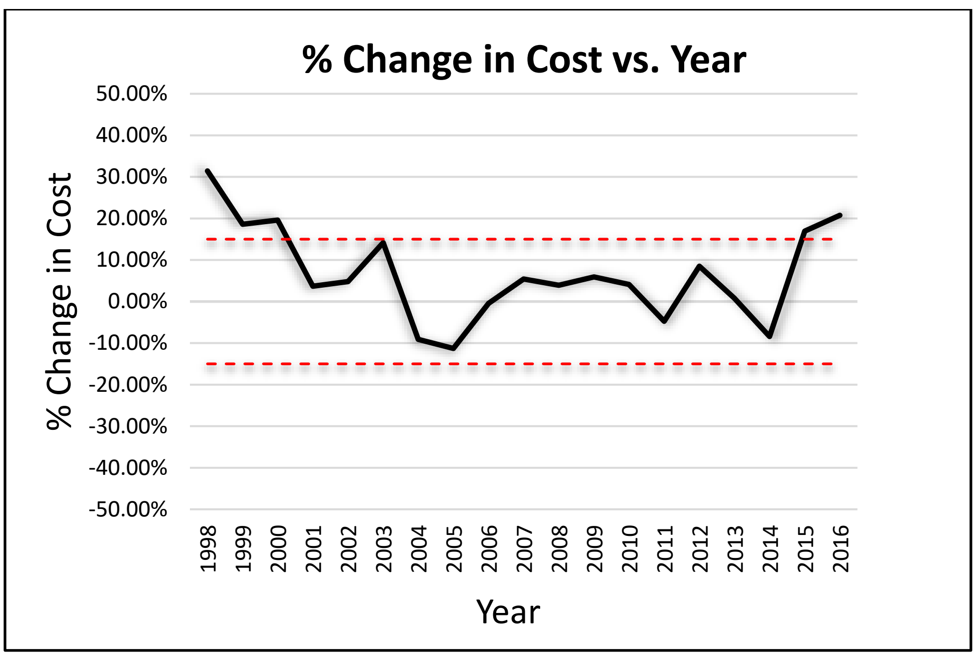


Figure 5. Notional Example of Stability Properties in O&S Costs

Lessons from Earned Value Management

While stability has essentially not been analyzed in O&S costs, Earned Value Management (EVM) is an area where stability properties have been researched. EVM is a tool the DoD uses to measure performance of acquisition contracts by tracking costs and schedule. One particular methodology to determine stability in EVM uses the Cost Performance Index (CPI). CPI is the ratio of cumulative scheduled costs over time to actual costs incurred over the same period. A CPI greater than 1.0 indicates that the project is under cost and favorable while a CPI of less than 1.0 indicates a project with cost overruns and unfavorable. Christensen and Payne state, “A stable CPI may thus indicate that the contractor’s estimated final costs of the authorized work, termed “Estimated at Completion,” are reliable.” (Christensen & Payne, 1992).

Petter (2015) expands on the research of Christensen and Payne by further investigating CPI and stability of earned schedule’s (ES) schedule performance index (SPI(t)) (Petter, Ritschel, & White III, 2015). Using the data EVM provides, his methodology includes three definitions of stability that have been researched in the field. The first definition states stability is when the range from the maximum to minimum CPI or SPI(t) is no greater than 0.2. The second definition declares stability when the final CPI is less than +/- 0.1 away from the CPI at a certain percent complete. The last definition of stability is when the final CPI is less than +/- 10% away from the CPI at a certain percent complete. (Petter et al., 2015).

These definitions of stability work for contracts because they have start and finish dates whereas O&S costs have a more perpetual nature. This is because it is easy to track percent complete in EVM while definitive end dates of O&S costs are uncertain. The second and third definitions utilize a final CPI value and their transferability to O&S costs may be difficult to determine without making assumptions on when a platform will be decommissioned. However, the first definition is closer in the line with the 15% definition implicitly given by the WSER. Using the first definition in Petter's work and the definition demonstrated by WSER, O&S cost data can be used to determine stability similar manner by using percent differences between years.

Chapter Summary

Over the years O&S costs have garnered more attention than in the past, however research still needs to catch up with this new interest. This literature review presented the Weapon System Acquisition Reform Act (WSARA) and how it is a major catalyst for the recent emphasis. Then provided were cost estimation guides authored by a variety of government agencies such as Air Force, OSD CAPE, and GAO. While the guides aim to help analysts estimate weapon system costs, there is room for improvement, especially with the tools used to estimate O&S costs. Also outlined is the previous research related to O&S costs, both before and after WSARA. Next the review introduces the Weapon System Enterprise Review (WSER) which is the primary reporting avenue of O&S costs for Air Force program managers. WSER hints slightly to stability by deeming programs deficient if the current cost is greater than 15% of the previous two-year average. This may or may not be a good metric for reporting and is one gap this research aims to fill. Stability in O&S cost estimates, an area that is completely lacking in the field is then discussed. Stability is important because it allows cost estimators to use previous year actual costs as a baseline for estimates and reduce uncertainty. There have been no research studies on stability properties regarding O&S costs but EVM does for CPI stability. EVM stability is not completely transferable to O&S costs but does provide a sound methodology to analyze stability in general. Chapter three will further expand on the methodology used to fill the stability gap for O&S costs.

III. Methodology

Chapter Overview

This chapter explains the methodologies used to gather and analyze the Operating & Support (O&S) cost data to determine stability properties and create a mathematical model to predict O&S costs. Initially, it discusses the source of the cost data, how it is collected, and how it is screened. Analysis includes programmatic information in addition to the O&S cost data. The first part of this methodology discusses processes to determine stability properties. This includes categorization and standardization of the data, the metrics used, how and why the data is truncated, mean percent differences, testing bounds to determine stability, and finally stability properties by aircraft type.

The second part of this methodology outlines the process to create a multiple regression model. Data from the first portion is used but needs further screening due to the addition of predictor variables. Once screened, the model building process is explained along with the diagnostics used to test assumptions. Finally, the process in which the model is validated and completed is discussed.

Operating and Support Cost Data

The main data used in this research includes the annual O&S costs for 44 aircraft programs. The research scope is limited to fixed wing and rotary wing aircraft in the Air Force inventory. Research is also limited to expenditures from 1996-2016 because the Air Force Total Ownership Cost (AFTOC) raw database does not contain data prior to 1996 or expenditures from 2017 at the time of this analysis. AFTOC provides costs in base-year dollars as well as then-year dollars. For this research, all costs used are in base-year 2016 to remove the effects of inflation. Air Force aircraft are the only programs included, however the same process can be applied to other DoD services with an adequate O&S cost database analogous to AFTOC.

Data Collection

AFTOC is a database that compiles the O&S costs of Air Force aircraft in one location and is the best source to obtain this data. Data can be pulled as a user-friendly pivot table created in Microsoft® Excel or a raw Excel database containing 233 columns and 15,243 rows of data. The pivot table allows the user to compile and screen data easier than the AFTOC raw database. However, the database was manipulated using R, an open source data science programming language. Using R and the pivot table together allowed the research team to manipulate the data in a way that stability and regression analysis could be completed.

The cost data is broken down into the six O&S cost element structures (CES) created by the Cost Analysis Improvement Group (CAIG) in 1992, revised in 2007, and revised again by the Cost Assessment & Program Evaluation (OSD CAPE) in 2014. Data is also compiled for a top-level cumulative cost that includes all CES. For the purposes of stability research, CES 6 (indirect costs) is not analyzed by itself because programs do not allocate these costs in a standardized fashion. The top-level costs used in stability and regression analysis do however include the indirect costs in the summation. Data from AFTOC also includes programmatic information such as the total active inventory (TAI) and flying hours per aircraft which is important for the standardization process in stability determination. Additional AFTOC programmatic data used for the regression analysis includes average age of aircraft, location of lead logistics center, operational mission type, and average unit cost, among others.

In addition to the data collected from AFTOC, Selected Acquisition Reports (SAR) provide programmatic data relevant to both stability and regression. The Initial Operational Capability (IOC) dates are needed and sourced from SARs to determine how many years it takes to reach stability from IOC. Deagel.com and AF.mil are also used for IOC dates and cross validation from SARs.

Screening of Base Data Set

AFTOC provides the Mission Design (MD) and Mission Design Series (MDS) for each aircraft which are used in the initial screening. For example, the F-15A's Mission Design is F-15 while its Mission Design Series is F-15A. The programs included in the research consist of MD programs that have a TAI of at least 10 in one of its years of data and at least 5 years of data for each MDS to be included. These two screening criteria ensure enough data points are available to form a trend and the aircraft chosen is significant enough to be analogous to other programs. The final screening is that IOC year is available so that the standardization process of "time from IOC" can be calculated. The final base data set consisted of 32 MDs and 57 MDSs however searching for IOC dates resulted in some MDSs being the same. In these cases, the MDSs are grouped with all other MDSs of the same MD with the same IOC date. Table 3 shows the screening steps to get to the final 44 programs used and Table 4 lists all the icluded programs by aircraft platform type. The final base data set is used for stability and regression analysis, although further independent screening is needed.

Table 3. Process of Screening Base Data Set

Screen	Remaining MD	Remaining MDS
AFTOC	158	274
MD TAI >10	62	146
MDS Years data >5	56	110
Available IOC date	32	57
		Programs
Grouped by IOC Date		44

Table 4. Programs Selected for Base Data Set by Aircraft Type

Fighter/Attack	**Reconnaissance**	**Helicopter**
A-10C	E-3B/C	HH-60G
A/OA-10	E-8C	MH-53J/M
F-117A	U-2S	UH-1H/N
F-15A	**Special Duty**	**Transport/Tanker**
F-15B	AC-130H/U	C-130E/H
F-15C	EC-130E/H	C-130J
F-15D	EC-130J	C-141B/C
F-15E	MC-130E/H	C-17A
F-16A	MC-130P	C-21A
F-16B	**Training**	C-5A/B
F-16C	T-1A	C-5M
F-16D	T-38A/C	CV-22B
F-22A	T-6A	HC-130P/N
Bomber	**UAV/Drone**	KC-10A
B-1B	MQ-1B	KC-135E/R
B-2A	MQ-9A	
B-52H	RQ-4B	

Part 1. Stability Analysis

Standardization and Categorization

Once the data is collected and initially screened, part 1 of this chapter explains the methodology to determine stability properties of aircraft. The data is standardized by cost per flying hour (CPFH) and cost per TAI (CPTAI) to control for the variance in hours flown or number of aircraft in the inventory. CPFH is the total annual cost divided by the total number of flying hours flown that same year. CPTAI is the total annual cost divided by the average number of aircraft in the inventory that year. These calculations are also used when analyzing the five different CESs as CPFH and CPTAI are broken into the five cost elements included in the research. The three cost categories the Weapon System Enterprise Review (WSER) breaks up O&S costs into are also inspected for stability. The WSER categories summarized in figure 4 of Chapter II are Centralized Asset Management (CAM) costs, Other Logistics Costs, and Other O&S Costs. For simplicity in our research, CAM costs are designated as WSER category 1, Other Logistics Costs are designated as WSER 2, and Other O&S costs are designated WSER category 3. Figure 5 in Chapter II outlines how the WSER sorts the 2007 CAIG cost categories into its three cost categories and is used in compiling the data. Another reason to standardize in this manner is that WSER asks to compare current O&S costs to the previous two-year average by TAI and CPFH. As a cross check, the Excel pivot table from AFTOC gives values for cost per TAI and CPFH, which are compared to the calculated values for the given year.

The "time from IOC" is calculated by subtracting the IOC year of a certain program from each year of the O&S cost data. All data is from 1996-2016 but the aircraft included are at different points in the sustainment phase. For example, in 2010 the C-17A is 17 years from IOC while the F-22A is only 5 years from IOC. When all data points are compiled, this allows the trends to be seen from "time from IOC" not just the 20-year period of data available for a specific program. The month of the IOC year is also ignored for simplicity and could be a slight limitation.

Stability Metrics

To test stability, we must first clarify the two-metrics used in the analysis. The first comes from the WSER while the second is more practical for cost estimators. Stability derived from the WSER is when a program incurs annual costs no greater than 15% of the previous two-year average costs. The WSER does not explicitly state stability but uses this calculation as a cut off for reporting deficient O&S costs. For example, if we want to assess the stability at year 1998, and the 1996 and 1997 annual costs were $1 million and $2 million respectively, then the two-year average cost would be $1.5 million. If 1998 incurred costs of $1.6 million then the percent difference would be:

$$|\%\ difference| = \left|\frac{\$1.6\ million - \$1.5\ million}{\$1.5\ million}\right| \times 100\% = 6.67\%$$

Given the WSER metric of stability, the 1998 cost would be considered stable because it is less than 15%. Recall that in the WSER, if a program's O&S costs are more than 15% above the two-year average it is considered "red" and deficient. The equation includes absolute values because the magnitude of the difference is all that is important for stability, not whether costs are trending up or down.

The second definition of stability that is useful to cost estimators is similar but uses the year to year percent cost difference rather than comparing costs to the two-year average. For this analysis, the six CAIG/CAPE cost categories are used. Again, only the first 5 CES are analyzed individually because indirect costs are levied on programs differently but CES 6 is used in total costs. A cost estimator wants to know when to start using actual costs as a basis for an estimate and will be able to do so once it is determined the program has stabilized. O&S cost estimates are developed using the CAIG/CAPE categories and any trends at these levels are valuable to the estimator. The methodology of when programs become stable is similar for the two metrics and the combinations of metric, cost category, and type of cost are summarized in Table 5. This results in 9 combinations for the WSER metric and 18 combinations for the Year to Year metric.

Table 5. Combinations of Stability Properties Analyzed

Metric	Category	Type of Cost
WSER (2 Year Avg)	WSER 1. CAM Costs WSER 2. Other Logistics Costs WSER 3. Other O&S Costs	Total Costs Cost Per Fly Hour (CPFH) Cost Per TAI (CPTAI)
Year to Year	Total O&S Cost CES 1. Unit-Level Manpower CES 2. Unit Operations CES 3. Maintenance CES 4. Sustaining Support CES 5. Continuing System Improvements	Total Costs Cost Per Fly Hour (CPFH) Cost Per TAI (CPTAI)

Truncation

The 44 selected programs have IOCs ranging from 1 to 57 years from IOC. The research is determining where stability occurs and we are truncating to OSD CAPE's notional Service Life Durations. Shown in table 6, the highest nominal service life duration between fixed wing and rotary wing is 40 years and is the point of truncation (Office of the Secretary of Defense; Cost Assessment and Program Evaluation, 2014). Jones (2014), used the OSD CAPE draft estimating guide for his research in finding the ratio of O&S costs to development costs and concluded services lives of 20-30 years for Fighters and Helicopters and 30-40 years for cargo, bomber, and tanker aircraft. Given these two determinations of service life, separate analysis is conducted for up to 30 years from IOC and from 30-40 years from IOC. This also allows the team to see if there is an aging effect on the data. The base data set has 765 program and year pairs (e.g. F-15A in

1998) while the truncated set has 681, which means only 10.98% of the data points are removed for truncation.

Table 6. Nominal Service Life Durations (OSD CAPE)

Commodity	Sub-Commodity	Service Life (Years)
Fixed Wing Aircraft	Fighter	20-25
	Cargo	25-30
	Tanker	40
	C4ISR	20-25
	CSAR	30
	Trainer	30-35
Rotary Wing Aircraft	Attack	20-30
	Utility	20-30
	Cargo	20-30

Mean Percent Difference for Years from IOC

Determining stability involves compiling all the years of cost data for all programs. Each data point consists of a time from IOC and a percent difference in cost from the previous year or two-year average. The mean percent difference in costs for each year from IOC is then calculated. For a notional example, at 10 years from IOC, the B-2A (2007) has a percent difference of 21.15%, C-130J (2009) is 11.56%, and F-22A (2015) is 18.34%. These programs reached 10 years from IOC at different calendar years but the mean percent difference for 10 years from IOC would be 17.02%. The mean percent difference is chosen rather than the median percent difference because means skew the research toward instability (high percentages), making the analysis more conservative. Once the mean percent difference is calculated for each year from IOC we can determine at which "time from IOC" the costs stabilize by testing bounds.

Testing Bounds

WSER metric: Research question #1 asks if the 15% bound generated by the WSER is a good metric or if there is a better, data driven number? To answer this question, we look at the means for each year from IOC for each cost combination and using a bound threshold, determine the year it falls within the bound. The process starts at a 20% bound and determines the first point from IOC the mean falls within the bound. The percent of time it stays within the 20% bound is calculated from the stability point to 30 years as well as the stability point to 40 years. If the mean percent difference falls within the 20% bound 80% of the time or more to 30 years we conduct the same process at the 15% bound. The percent stable to 40 years is not used in the selection of the best bound because there may be some aging affect. The process is repeated for the 10% and 5% bound if applicable. If a cost combination is not stable 80% of the time, then the previous bound is selected as the best bound. 80% is the cutoff selected because O&S costs have an uncertain nature, and it is highly unlikely that they will be stable 100% of the time. To provide a data driven number, the mean, standard deviation, and median are calculated for the values from the stability point to 30 years from IOC. The same descriptive statistics are also calculated for years 30-40 to see if any aging affects are present. This is needed because combinations may have different stability points at certain bounds.

Year to year metric: The process for the year to year metric is identical but includes more robust results. The WSER needs to know stability points for reporting present values, whereas cost estimators are making estimates in the out-years. The process starts at the 20% bound and determines the first point from IOC that the mean falls within the bound. The percent of time that it stays within the 20% bound is calculated from the stability point to 30 years as well as the stability point to 40 years. If the mean percent difference across all years falls within the 20% bound 50% of the time or more we conduct the same process at the 15% bound. Being stable 50% of the time is our cut off because it is the point where the means are either more stable or more unstable. This process is completed for all 18 combinations of the year to year metric down to the 5% bound, if applicable.

Once the points of stability are determined for each combination and at each bound, the best bound for each combination is chosen to run descriptive statistics on. Like the WSER metric, the best bound is chosen as the last bound to have at least 80% stability from the point that it falls within the bound to 30 years from IOC. If the means do fall within a bound 100% of the time it is likely that the bound is too wide which isn't helpful to estimators or decision makers. The Year to Year metric includes summary statistics for the best bound but also illustrates the properties at tighter bounds that don't exhibit stability 80% of the time should a decision maker be willing to take more risk.

Stability Properties by Aircraft Type

Research question #3 aims to determine if stability properties vary by aircraft type. When comparing by aircraft type this research focuses on the Year to Year metric of stability because the WSER uses the same metric for all programs regardless of the aircraft platform type. Conversely, cost estimators want to know the stability properties of the type of aircraft being estimated. The process to find the mean percent difference by year from IOC is the same but is calculated only with aircraft of a certain type. The aircraft are broken into the 8 operational mission types given by AFTOC and include

Bomber, Fighter/Attack, Helicopter, Reconnaissance, Special Duty, Training, Transport/Tanker, and Unmanned Aerial Vehicles (UAV). Once mean percent differences are found, the bounds are tested. It is important to note that splitting the 44 programs into 8 categorizes drastically reduces the number of data points for each aircraft type and is summarized in Table 7. Furthermore, an aircraft type that has a small number of programs may not have data points all the way to 30 or 40 years from IOC and is adjusted depending on the available data. A table of properties at each bound is created as well as descriptive statistics if viable.

Table 7. Data Points Used to Calculate Mean for Each Year from IOC by Aircraft

Years from IOC	Bombers	Fighter/ Attack	Helo	Recon	Special Duty	Training	Transport/ Tanker	UAV
1	1	2	0	1	2	1	3	3
2	1	2	0	2	2	1	3	3
3	1	2	0	2	2	1	4	3
4	1	2	0	2	2	2	4	3
5	1	2	0	2	3	2	4	3
6	1	2	0	2	3	2	3	3
7	1	3	0	2	3	2	3	3
8	1	3	0	2	3	2	2	3
9	1	3	0	2	3	2	2	3
10	2	2	0	2	4	2	2	1
11	2	2	1	2	4	2	2	1
12	2	1	1	2	4	2	3	0
13	2	1	1	2	4	2	3	0
14	2	2	2	2	4	2	3	0
15	2	4	2	2	4	2	4	0
16	2	4	2	2	4	1	4	0
17	2	8	2	2	4	1	4	0
18	2	8	2	2	4	1	3	0
19	2	8	2	3	4	1	3	0
20	1	9	2	3	4	1	3	0
21	1	11	2	2	4	1	3	0
22	1	11	2	2	3	1	4	0
23	1	11	1	1	3	1	4	0
24	1	11	1	1	3	1	3	0
25	1	11	2	1	3	0	3	0
26	1	11	2	1	2	0	4	0
27	1	10	2	1	2	0	4	0
28	1	9	2	1	2	0	4	0
29	1	8	2	1	2	0	4	0
30	1	7	2	1	2	0	4	0
31	0	7	2	1	1	0	5	0
32	0	7	2	1	1	0	5	0
33	0	7	2	1	1	0	4	0
34	0	7	2	1	0	0	4	0
35	1	6	1	1	0	1	4	0
36	1	2	1	1	0	1	3	0
37	1	2	1	1	0	1	3	0
38	1	0	1	1	0	1	3	0
39	1	0	1	1	0	1	4	0
40	1	0	1	0	0	1	4	0
Total	**46**	**208**	**49**	**62**	**96**	**42**	**138**	**29**

Part 2. Multiple Regression Analysis

Predicting O&S Costs for a Given Year

The second part of this chapter describes the process to create a mathematical model to predict the top-level O&S costs per aircraft. A robust multiple regression model is useful for cost estimators as a cross check to other cost estimation methods. The starting point for this regression model is a Congressional Budget Office (CBO) model created in 2001 (Congressional Budget Office, 2001). In their research, CBO built off the RAND model and used 68 observations. The model included 17 programs and 4 years of O&S cost data pulled from the AFTOC database. The final equation from CBO is shown in Equation 1. CBO had success but a model with 20 years of O&S cost data and 44 programs provides a much more robust model. In addition to being a top-level cross check, this model can be used for rough order of magnitude (ROM) estimates if no other O&S cost data is available for a certain program.

Equation 1:

$$ln(COST) = \alpha + \beta_1 * AGE + \beta_2 * ln(TEMPO) + \beta_3 * ln(PAUC) + \beta_i * Ydummies + \varepsilon$$

Where:

COST	=	operating costs/inventory
α	=	intercept term
AGE	=	average annual age/100
TEMPO	=	annual flying hours/inventory
PAUC	=	procurement average unit cost
Ydummies	=	dummy variables for years

Response Variable

The dependent variable in this regression analysis is the cost per TAI. This is a total O&S cost that includes all six O&S cost element structures. TAI is the average total aircraft in the inventory for a specified year.

Predictor Variables

The AFTOC database provides O&S costs as well as programmatic information that is used to create independent, predictor variables. Examples of programmatic data provided in the database include average age of aircraft, location of lead logistics center, operational mission type, average unit cost, among others discussed in Chapter IV. Results from the stability analysis provide predictor variables for the years from IOC and point of stability.

Rescreening of Base Data Set

The base data set of 44 programs is used for this portion of analysis, however given the added variables, it must be rescreened to properly be used for regression. Note, no truncation of the years from IOC is included for regression to provide for an all-inclusive model. The only cost being used in this analysis is the total cost per TAI, the response variable. The first screen is to remove data points that are years before IOC or the year of IOC which ensures all observations start at 1 year from IOC. Each program and "years from IOC" pair must also have only one value for each potential predictor variable. This screen resulted in five grouped programs that had two different unit-costs and one grouped program with two different logistics centers. The five grouped programs with different unit-costs include C-141B/C, KC-135E/R, MH-53J/M, T-38A/C, and UH-1H/N. These programs had major overhauls at some point in their service life that created a new aircraft variant (MDS) and resulted in removal from the data set. The program with two logistics centers is the EC-130E/H and is included in the regression data set because location of logistics center is a binary variable that may influence the O&S cost. The final screen necessary for multiple regression is that all potential variables have a specified value, a screen that JMP completes automatically when building a model. The final regression data set has 708 rows of data however the final automatic screen that JMP completes results in 609 data points used for modeling. Table 8 summarizes the rescreening steps of the base data set used for regression analysis.

Table 8. Rescreening of Base Data Set

Screen	Programs	Observations Remaining
Base Data Set	44	994
Years from IOC < 1	44	892
Duplicate Unit Costs	39	708
Has value for each variable	39	609

Validation Pool

A portion of the data is set aside from the regression model to serve as a validation pool. For this research, we randomly choose 80% of the final data set to create the multiple regression model and 20% to validate the model. The accuracy of the model is tested using the 20% validation pool. To complete this, a random uniform distribution variable ranging from 0 to 1 is first created in JMP Pro®. Then a variable called Model/Test is created and using the if function, any data row that has the random uniform variable value above 0.8 is designated Test while anything at or below 0.8 is designated Model. Of the 609 data points included in the model, 484 (79.47%) were designated as Model and 125 (20.53%) are designated as Test.

Model Building Process and Diagnostics

Model building is an iterative process and doesn’t follow one prescribed path. For the purposes of this research, we use the stepwise function in JMP to determine which predictor variables are initially included in the model. We utilize the stepwise function in JMP and a p-value threshold of 0.05 as the threshold to enter or exit model. The mixed direction option is used in lieu of forward or backward options because the variable needs to be significant to enter the model and remain significant when other variables are input. Variables may or may not be included in the model depending on individual significance and contingent on passing regression diagnostics. The diagnostics that the model must pass are Holm-Bonferroni Correction, Variance Inflation Factors, Cook's D test, analysis of studentized residuals, Shapiro-Wilk test, and Breusch-Pagan test. Once all diagnostics are passed, we test the preliminary model comprised of 80% of the data points to the validation pool of 20%. If the results are similar, as determined by mean absolute percent error (MAPE) and median absolute percent error (MdAPE), then the final model is validated and remade using all data points.

Holm-Bonferroni Correction

Holm-Bonferroni correction is where the accepted alpha value must be divided by the total number of variables in the model to counteract the problem with multiple comparisons. If the model has an alpha of 0.05 and there are 5 variables then each variable must have a p-value of less than 0.01. This ensures that every variable is truly a predictor variable and reduces type 1 error of false positives.

Variance Inflation Factors

When creating any regression model, we must check variance inflation factor (VIF) scores of the predictor variables. This gets rid of multicollinearity that may exist between the factors. If two factors are linearly dependent, then only one is needed as a predictor variable. "A VIF of 10 suggests that it is large enough to indicate a problem" (Stine, 1995).

Cook’s Distance Test

Overly influential observations may skew the results of the model. Cook’s Distance Test (Cook’s D) is one method to test for these skewing data points. Data points that may be overly influential may inform the model builder that more data points are needed for that specific range or that the data point may be an error. When completing the Cook’s D test, we screen for data points with a value higher than 0.5 for potential exclusion.

Studentized Residuals

In addition to checking for overly influential points and areas, we also check for outliers within the data. A histogram of the studentized residuals determines which points are considered outliers and can be removed. If there are too many points outside of three standard deviations then they may not be considered outliers and the data could just not be normally distributed.

Shapiro-Wilk’s Test

The multiple regression model must also have its residuals pass the assumption of being normally distributed. The Shapiro-Wilk’s test determines whether the data set can be considered normally distributed. In this research, a threshold of $\alpha = 0.05$ is used to ensure the p-values of our predictor variables are valid. The null hypothesis in the Shapiro-Wilk’s test is that the model has normally distributed residuals. If a p-value is higher than 0.05, then our model’s data passes the assumption of normality.

Breusch-Pagan Test

Next, we test our final model assumption of constant variance of the error term using the Breusch-Pagan test. Heteroscedasticity is present when the predictor variables do not exhibit constant variance. The most robust regression models have as close to equal constant variance as possible. Similar to Shapiro-Wilk's test, Breusch-Pagan's null hypothesis is that there is constant variance. Passing the assumption of constant variance using the Breusch-Pagan test requires a p-value above 0.05. If constant variance is not present, natural logarithmic transformation of the response or predictor variables can be used to reduce heteroscedasticity.

Multiple Regression Analysis

The last step of our model building process is finalizing the model. Once all prior criteria are met, the structure of the finalized model reflects the standard linear multiple regression equation, shown in Equation 2 (McClave et al., 2001:557).

Equation 2:

$$Y_i = \beta_0 + \beta_1 X_{1i} + \beta_2 X_{2i} \ldots + \beta_k X_{ki} + \varepsilon_i$$

Where:
Y_i - Outcome of Dependent Variable (response) for *ith* experimental/sample unit
X_i - Level of Independent (predictor) variable for *ith* experimental/sample unit
$\beta_0 + \beta_1 X_{1i}$: Linear /systematic relation between *Yi* and *Xi* (conditional mean)
β_0: Mean of *Y* when *X*=0 (*Y*-intercept)
β_1: Change in mean of *Y* when *X* increases by 1 (slope)
ε_i- Random error term

The descriptive performance measures of the multiple regression model are R^2 and adjusted R^2 and statistical measure how well the data fits the regression line. Adjusted R^2 is affected by the number of predictor variables in the model while R^2 is not. An R^2 of 1 explains all the variance while 0 indicates the model explains no variance in the data. Adjusted R^2 only increases when the addition of a variable increases R^2 as well and ensures that the predictability of added variables warrants an increase in complexity. Equation 3 is the calculation of Adjusted R^2 (McClave et al., 2001:557).

Equation 3:

$$Adusted\ R^2 = 1 - \left[\frac{(n-1)}{n-(k+1)}\right](1-R^2)$$

Where:
n= the number of data points
k= the number of independent variables in the model

Validation of Multiple Regression Model

Once the model has been created it is tested against our 20% validation pool for accuracy. The absolute percent error (APE) is calculated by subtracting predicted model values from actual values and then dividing by the actual value. Recall MAPE and MdAPE are mean and median values for APE. Once MAPE and MdAPE are calculated for the model set (80%) and test set (20%), we compare results for consistency. Then a bivariate plot of actual values vs. predicted values for the model and test sets is utilized to compare the regression line of each graph. If the model set and test set compare similarly to each other using MAPE, MdAPE, and bivariate plots, then the model is validated. The last step is to compile all 609 data points back into a final, complete model.

Chapter Summary

This chapter describes the research methodology used to collect and screen data as well as analyze for stability properties and complete regression analysis. The research team uses AFTOC O&S cost data and IOC years from multiple sources for stability analysis and adds other AFTOC programmatic information for regression analysis. The methodologies present are justified based on prior research in addition to some assumptions that had to be made based on the available data. Chapter IV presents the results of the analysis using the methodologies presented in this chapter.

IV. Results and Analysis

Chapter Overview

This chapter presents the results of the methodology outlined in Chapter III. The chapter is organized into two sections of results. The first section includes analysis of stability properties while the second section displays the developed multiple regression model to predict annual O&S cost per total active inventory (Cost per TAI). Stability is determined for the Weapon System Enterprise Review (WSER) metric as well as the Year to Year metric. The process starts with finding mean percent differences of costs given a time from Initial Operational Capability (IOC), determining the appropriate bound, and running descriptive statistics to provide a data driven stability point. Analysis of stability properties by aircraft type is limited by sample size but provides the results from testing bounds and descriptive statistics where appropriate.

The multiple regression section includes the results from creating a preliminary model, diagnostic tests used to analyze the model, and a final model to predict total O&S cost per TAI. Finally, the model is tested on the 20% validation pool using Mean Absolute Percent Error (MAPE), Median Absolute Percent Error (MdAPE), and regression fitting of bivariate actual vs. predicted plots to measure the performance of the model. The explanatory power is assessed using R^2 and adjusted R^2 values.

Part 1. Stability Analysis

Recall from Chapter III that the stability point is determined for both the WSER and Year to Year metrics starting with the 20% bound. If a cost combination is 80% stable at the 20% bound further investigated to the 15%, 10%, and 5% bounds when applicable. Stability is found when the mean percent difference at a given time from IOC falls within the tested bound. Figure 6 displays the number of programs used in the calculations of means for each year from IOC. Note that these are the number of programs used in the calculation of the total O&S category; the number of programs utilized in the calculation for other categories may deviate slightly from Figure 6 due to missing data points.

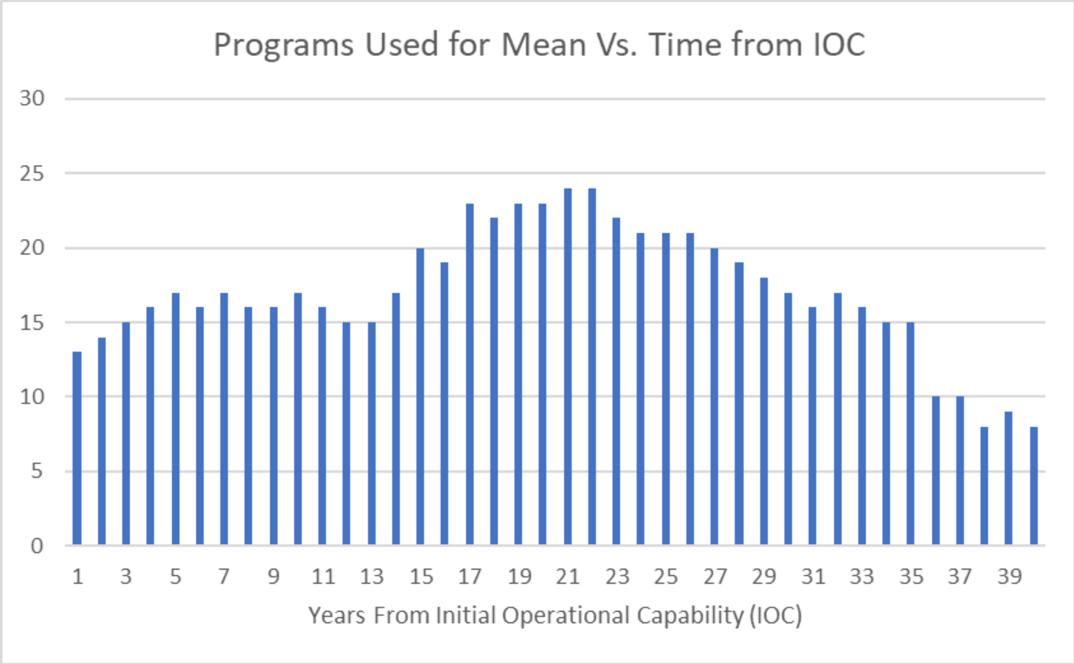


Figure 6. Number of Programs Used to Calculate Mean % Difference

Determining Stability For WSER

Research question #1 aims to determine a data driven point of stability for use in the WSER. The process starts by calculating the mean percent difference of each time from IOC for the nine combinations included in the WSER metric of stability. WSER stability is measured by calculating percent differences from the previous two-year average. Table 9 summarizes the mean percent differences for all WSER combinations. Note that there are no data points for the first year because the calculation requires the two-year prior average. Using table 1 and the 20% bound allows us to see the point of stability for each cost combination. In our analysis, only cost combinations WSER 2, CPTAI WSER 2, and CPTAI WSER 3 have stability 80% of the time at the lower 15% bound. CPFH WSER 1 and CPTAI WSER 1, which are both Centralized Asset Management (CAM) costs did not reach 80% stability at the 20% bound. No cost combinations make it to the 10% or 5% bound for the WSER.

Table 9. Mean Percent Differences for WSER Combinations

Years from IOC	WSER 1	WSER 2	WSER 3	CPFH WSER 1	CPFH WSER 2	CPFH WSER 3	CPTAI WSER 1	CPTAI WSER 2	CPTAI WSER 3
1									
2	136.4%	117.9%	92.2%	76.4%	28.9%	37.6%	70.4%	38.3%	30.2%
3	116.1%	118.3%	158.0%	32.0%	39.3%	36.7%	53.2%	58.9%	67.1%
4	1975.6%	43.7%	83.1%	377.8%	19.9%	18.0%	1314.2%	20.6%	37.3%
5	490.4%	29.4%	44.0%	313.3%	19.9%	23.0%	366.5%	20.3%	26.2%
6	27.9%	27.7%	30.3%	24.2%	21.6%	18.5%	16.4%	18.0%	12.1%
7	26.1%	20.8%	20.9%	19.8%	19.4%	15.4%	21.1%	14.3%	11.1%
8	24.1%	27.6%	26.7%	18.3%	25.9%	23.5%	17.7%	17.7%	22.7%
9	31.0%	18.9%	18.7%	24.1%	11.9%	13.8%	27.2%	13.1%	12.8%
10	18.1%	14.9%	16.7%	12.8%	17.0%	9.1%	12.1%	11.5%	10.2%
11	23.3%	15.4%	18.7%	20.6%	13.8%	12.4%	20.7%	11.1%	14.0%
12	21.5%	13.2%	19.2%	25.8%	10.7%	11.7%	19.6%	7.6%	14.0%
13	41.8%	13.1%	13.3%	40.3%	13.2%	15.5%	35.9%	9.8%	12.6%
14	15.8%	13.2%	14.7%	12.9%	13.7%	16.6%	15.3%	12.2%	14.7%
15	16.8%	18.8%	11.7%	18.4%	19.6%	13.6%	17.2%	17.3%	10.4%
16	24.1%	12.3%	11.0%	22.3%	8.7%	8.1%	24.7%	12.0%	10.2%
17	19.7%	11.7%	8.8%	23.6%	14.3%	12.2%	21.2%	11.4%	9.0%
18	10.9%	12.1%	9.9%	9.5%	12.5%	9.1%	11.5%	11.6%	9.0%
19	14.0%	9.9%	14.2%	20.6%	10.5%	14.4%	16.1%	8.6%	13.7%
20	10.0%	8.4%	9.4%	13.5%	11.2%	12.0%	12.0%	7.8%	9.9%
21	16.9%	9.9%	11.5%	22.9%	16.8%	15.0%	19.5%	12.0%	13.6%
22	12.4%	11.7%	10.3%	12.2%	12.2%	11.3%	12.8%	12.1%	11.5%
23	14.5%	8.1%	10.8%	19.2%	13.6%	9.3%	16.9%	7.9%	8.6%
24	17.3%	15.2%	15.6%	16.7%	20.7%	15.8%	18.7%	15.4%	15.8%
25	12.6%	13.3%	11.2%	10.6%	15.2%	10.8%	10.3%	13.3%	10.9%
26	14.1%	11.9%	12.3%	19.4%	23.3%	13.6%	13.5%	12.0%	8.0%
27	16.9%	9.8%	15.9%	15.0%	13.4%	21.5%	14.8%	7.8%	18.6%
28	19.0%	12.6%	19.1%	13.4%	20.0%	32.4%	15.6%	10.1%	22.9%
29	17.7%	16.6%	17.8%	20.0%	14.5%	17.9%	12.3%	13.2%	14.4%
30	15.9%	12.4%	30.3%	16.0%	15.5%	27.8%	13.1%	8.1%	25.2%
31	13.5%	11.8%	16.0%	11.1%	10.5%	14.8%	10.0%	6.6%	10.8%
32	15.3%	14.6%	20.5%	13.9%	13.5%	13.4%	10.7%	5.6%	19.5%
33	19.4%	16.6%	22.9%	15.7%	13.7%	18.8%	17.3%	5.5%	14.4%
34	21.0%	19.3%	158.1%	16.0%	14.1%	351.9%	10.4%	11.6%	639.1%
35	24.8%	18.3%	33.5%	28.1%	22.1%	35.6%	25.2%	11.5%	25.6%
36	15.8%	11.8%	15.9%	9.4%	9.9%	8.6%	14.5%	10.1%	12.7%
37	19.1%	15.3%	50.6%	14.6%	13.0%	54.3%	19.1%	9.2%	50.6%
38	14.1%	15.2%	16.5%	13.2%	13.2%	18.3%	12.3%	9.2%	22.9%
39	21.6%	18.8%	20.6%	22.4%	13.1%	16.6%	16.0%	15.4%	13.0%
40	31.1%	22.6%	25.2%	23.6%	16.3%	20.3%	26.7%	17.3%	19.9%

With the point of stability determined at the appropriate bound, the mean, standard deviation, and median of the stable values are calculated to provide insight on what the stability bound may actually be. This is calculated from the point of stability to 30 years from IOC and from 30 to 40 years to check for aging effects. Results are displayed in Table 10. In addition to the descriptive statistics is the percent of time that the costs stay within the chosen bound. In six of the nine WSER combinations there appears to be an aging affect where the percent of time it stays within the bound decreases past 30 years. The means and medians on five of those six also are larger which further shows some aging affect.

Table 10. Summary Statistics for WSER Combinations

	WSER 1	WSER 2	WSER 3	CPFH WSER 1	CPFH WSER 2	CPFH WSER 3	CPTAI WSER 1	CPTAI WSER 2	CPTAI WSER 3
Stable After (Years)	9	9	8	6	3	3	5	6	5
Bound Selected	20%	15%	20%	20%	20%	20%	20%	15%	15%
Stable-30									
Mean	17.77%	12.59%	14.59%	18.67%	15.88%	15.64%	17.44%	11.58%	13.43%
Std Dev	6.62%	2.63%	4.90%	6.43%	4.35%	5.84%	5.71%	2.83%	4.58%
Median	16.91%	12.39%	13.74%	18.78%	14.49%	14.39%	16.41%	11.78%	12.58%
% Stable to 30	80.95%	80.95%	95.45%	62.50%	81.48%	81.48%	76.00%	87.50%	80.00%
30-40									
Mean	19.57%	16.43%	37.97%	16.80%	13.94%	55.27%	16.23%	10.20%	82.85%
Std Dev	5.43%	3.39%	43.50%	5.97%	3.37%	105.07%	5.96%	3.93%	195.77%
Median	19.23%	15.97%	21.75%	15.13%	13.35%	18.58%	15.27%	9.68%	19.69%
% Stable to 40	74.19%	64.52%	75.00%	64.71%	83.78%	75.68%	77.14%	85.29%	71.43%

Determining Stability for Year to Year Metric

Stability using the year to year metric is calculated the same but with an added step to show the best bound selection and properties at tighter bounds. Table 11 shows the mean percent differences for cost per TAI at each year from IOC, up to 40 years. The table displays total cost per TAI and the 5 O&S cost element structures (CES) per TAI. Tables for total O&S cost and cost per fly hour (CPFH) are attached in Appendix A and demonstrate similar characteristics. CES 4 and 5 do not fall under the 20% threshold at any point and are removed from further analysis in this chapter. While it may seem troublesome to remove two of the five categories, O'Hanlon (2018) determined that CESs 1, 2, and 3 make up the majority of O&S costs with a mean of 82.39% and median of 80.53%. (O'Hanlon, 2018).

Table 11. Mean Percent Difference for Cost per TAI

Years from IOC	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3	CPTAI CES 4	CPTAI CES 5
1	644.8%	847.3%	2704.0%	246.4%	232.7%	37.8%
2	27.0%	24.7%	43.3%	60.6%	51.1%	100.7%
3	39.2%	207.0%	25.7%	70.0%	144.9%	1360.0%
4	13.3%	15.6%	15.8%	35.4%	945.8%	157.0%
5	23.5%	11.1%	17.2%	21263.8%	53.0%	40.3%
6	6.3%	11.9%	25.7%	12.0%	68.7%	117.2%
7	10.0%	14.5%	14.7%	20.7%	232.8%	70.7%
8	11.0%	11.4%	21.8%	24.6%	71.0%	46.6%
9	11.0%	7.3%	25.2%	18.2%	112.6%	63.5%
10	8.7%	7.4%	11.4%	18.5%	201.9%	56.0%
11	9.6%	8.3%	16.1%	20.8%	91.0%	91.2%
12	6.6%	6.9%	10.9%	11.7%	21.0%	25.8%
13	12.5%	9.5%	6.3%	36.4%	43.3%	33.4%
14	7.4%	7.1%	11.6%	11.9%	198.0%	54.8%
15	8.4%	8.9%	17.8%	22.3%	145.1%	27.9%
16	10.6%	8.4%	10.5%	25.2%	310.3%	94.0%
17	7.2%	6.8%	12.8%	13.8%	58.0%	39.7%
18	9.1%	7.2%	14.0%	22.2%	90.9%	48.4%
19	5.1%	4.5%	8.8%	12.3%	58.5%	37.3%
20	6.4%	8.2%	9.2%	14.7%	73.7%	31.0%
21	10.5%	7.9%	13.2%	21.4%	93.7%	54.5%
22	8.8%	8.3%	13.3%	18.0%	102.0%	113.4%
23	6.4%	6.7%	11.2%	15.6%	45.3%	43.6%
24	8.4%	13.2%	10.1%	17.6%	133.0%	149.5%
25	7.4%	11.2%	9.1%	10.1%	24.2%	45.9%
26	9.3%	9.0%	10.1%	17.1%	33.3%	22.6%
27	6.1%	5.9%	13.0%	12.5%	57.3%	45.8%
28	8.8%	10.9%	6.6%	16.8%	16.5%	53.7%
29	6.4%	8.9%	13.1%	13.3%	29.3%	178.5%
30	9.0%	6.9%	12.4%	14.1%	40.6%	278.9%
31	5.4%	4.1%	9.7%	9.4%	51.8%	26.2%
32	6.5%	5.5%	15.2%	10.9%	54.6%	35.0%
33	8.0%	5.7%	9.9%	15.3%	29.6%	94.0%
34	10.7%	9.0%	18.8%	12.4%	42.1%	7010.8%
35	13.3%	12.9%	12.4%	26.9%	43.5%	94.6%
36	7.5%	4.3%	11.6%	15.9%	28.9%	69.9%
37	8.7%	7.4%	12.8%	20.8%	39.6%	45.5%
38	11.5%	10.7%	13.8%	18.2%	45.3%	228.1%
39	7.8%	10.9%	12.4%	15.6%	36.3%	85.0%
40	11.6%	9.5%	16.1%	17.5%	58.7%	188.4%

The next step is to start at the 20% threshold and determine a stability point. Then the percentage of time that the means stay within the bound is calculated. If means demonstrate more than 50% stability at the 20% bound it is checked at the 15% bound. This process is repeated down to the 5% bound when applicable. The percent stable is also calculated from the point of stability to 40 years from IOC to detect any aging affects. After all bounds are explored, the best bound for stability is determined by selecting the tightest bound that had at least 80% stability. Table 12 shows all calculations of percent stable and highlighted is the best bound selection. Once the best bound is selected, summary statistics are calculated for each combination to include mean, standard deviation, and median as displayed in Table 12.

Table 12. Exploration of Bounds and "Best" Bound Selection

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30	# Outside Bound (40)	% Stable to 40
Total O&S	20%	Yes	5	1	96.00%	1	97.14%
	15%	Yes	5	2	92.00%	6	82.86%
	10%	Yes	11	5	73.68%	13	55.17%
	5%	No	18	11	8.33%	21	4.55%
Total CES 1	20%	Yes	6	1	95.83%	1	97.06%
	15%	Yes	7	1	95.65%	4	87.88%
	10%	Yes	9	5	76.19%	12	61.29%
	5%	No	18	11	8.33%	21	4.55%
Total CES 2	20%	Yes	3	5	81.48%	6	83.78%
	15%	Yes	9	3	85.71%	9	70.97%
	10%	No	12	14	22.22%	24	14.29%
	5%	No	N/A				
Total CES 3	20%	Yes	5	7	72.00%	12	65.71%
	15%	No	11	10	47.37%	18	37.93%
	10%	No	N/A				
	5%	No	N/A				
CPFH Total	20%	Yes	3	0	100.00%	0	100.00%
	15%	Yes	3	4	85.19%	5	86.49%
	10%	Yes	13	6	64.71%	9	66.67%
	5%	No	0	30	0.00%	40	0.00%
CPFH CES 1	20%	Yes	3	3	88.89%	4	89.19%
	15%	Yes	3	7	74.07%	10	72.97%
	10%	No	8	16	27.27%	25	21.88%
	5%	No	N/A				
CPFH CES 2	20%	Yes	2	4	85.71%	4	89.47%
	15%	Yes	3	6	77.78%	6	83.78%
	10%	No	24	5	16.67%	15	6.25%
	5%	No	N/A				
CPFH CES 3	20%	Yes	8	8	63.64%	10	68.75%
	15%	No	13	14	17.65%	20	25.93%
	10%	No	N/A				
	5%	No	N/A				
CPTAI Total	20%	Yes	3	1	96.30%	1	97.30%
	15%	Yes	3	1	96.30%	1	97.30%
	10%	Yes	5	5	80.00%	9	74.29%
	5%	No	0	30	0.00%	40	0.00%
CPTAI CES 1	20%	Yes	3	0	100.00%	0	100.00%
	15%	Yes	4	0	100.00%	0	100.00%
	10%	Yes	8	3	86.36%	6	81.25%
	5%	No	18	11	8.33%	19	13.64%
CPTAI CES 2	20%	Yes	3	3	88.89%	3	91.89%
	15%	Yes	6	4	83.33%	7	79.41%
	10%	No	12	13	27.78%	21	25.00%
	5%	No	N/A				
CPTAI CES 3	20%	Yes	5	8	68.00%	22	37.14%
	15%	No	5	15	40.00%	22	37.14%
	10%	No	N/A				
	5%	No	N/A				

For further clarification in the process, we investigate CPTAI CES 1 and CPTAI CES 2 because they have different bounds selected and different times to stability. As shown in Table 4, both pass through the 20% threshold after 3 years from IOC with CES 1 remaining within the bound 100% of the time to 30 years and CES 2 88.89% of the time. At the 15% bound, CES 1 reaches stability after 4 years with 100% stability to 30 years and CES 2 reaches stability after 6 years with 83.33% stability. At the 10% bound, CES 1 reaches stability after 8 years with 86.3% stability while CES passes the threshold after 12 years and only remains stable 27.78% of the time to 30 years. This means that CPTAI CES 1's best bound is 10% while CPTAI CES 2's best bound is 15%. Using the best bound selection, Table 5 shows that CPTAI CES 1 has a mean of 8.15% and median of 8.06% while CPTAI CES 2 has mean of 12.63% and median of 12.03%. The use of the bound selection and descriptive statistics provide cost estimators with a clearer picture on the stability properties for each cost combination.

Looking at Table 13, several important conclusions can be drawn from the data. For instance, CES 1 (manpower) and 2 (unit operations) have much lower means and medians than CES 3 (maintenance) which could be because manpower and pay is fairly constant. Flight hours can be mandated by law and have a more consistent nature to them as well. Maintenance is much harder to predict and could be why less stability is exhibited in CES 3 across all cost combinations. The cost type that has the tightest best bounds looks to be cost per TAI and it also has lower means and medians than the other two cost categories. In addition to the conclusions across cost type and cost categories, there appears to be aging affects in total costs and cost per TAI but not for cost per fly hour combinations. The means and medians for these groups rise and the percent stable from 30 years to 40 years from IOC decrease. The opposite is true with CPFH, where means and medians decrease while percent stable increases.

Table 13. Summary Statistics for Year to Year Metric (Excluding CES 4 & 5)

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	5	7	9	5	3	3	2	8	5	8	6	5
Bound Selected	15%	15%	15%	20%	15%	20%	20%	20%	10%	10%	15%	20%
Stable-30												
Mean	10.24%	9.75%	13.27%	18.30%	11.44%	13.39%	12.42%	19.43%	8.44%	8.15%	12.63%	17.68%
Std Dev	3.64%	3.53%	5.41%	6.31%	3.20%	4.38%	4.90%	6.06%	1.89%	1.89%	4.32%	5.80%
Median	9.31%	9.09%	12.49%	17.69%	10.79%	12.16%	11.80%	18.35%	8.71%	8.06%	12.03%	17.06%
% Stable to 30	92.00%	95.65%	85.71%	72.00%	85.19%	88.89%	85.71%	63.64%	80.00%	86.36%	83.33%	68.00%
30-40												
Mean	13.05%	12.21%	16.37%	18.62%	9.55%	13.45%	8.77%	17.36%	9.10%	7.99%	13.27%	16.30%
Std Dev	3.21%	4.09%	3.34%	3.57%	3.39%	3.90%	2.04%	5.21%	2.55%	3.05%	2.81%	5.09%
Median	13.58%	13.68%	18.28%	20.63%	8.98%	12.99%	8.56%	15.49%	8.67%	8.95%	12.76%	15.90%
% Stable to 40	82.86%	87.88%	70.97%	65.71%	86.49%	89.19%	89.47%	68.75%	74.29%	81.25%	79.41%	37.14%

Stability Properties by Aircraft Platform Type

Research question #3 asks if there are any differences in stability properties based on aircraft type. The sample size to calculate means drops drastically when splitting the 44 programs up in 8 different categories which limits the fidelity of inferential statistics. In addition, not all aircraft platform types have data points for years from IOC of between 1 and 40. For this reason, bounds testing and descriptive statistics provided for aircraft platform type is catered to the available data of the aircraft type. Cutoffs and assumptions are also made in conjunction with the available data. In addition, CES 4 and 5 are removed from analysis due to the instability of these categories found in the aggregate results. Summary statistics for each type of aircraft are presented in Tables 14-21 while the selections for best bound are included in Appendix B.

Bombers

Bombers only include the B-1B and B-2A because B-52A has data from years 36 to 55. Data for the two programs only goes to 30 years from IOC which eliminates testing to 40 years for this category. Table 14 illustrates the summary statistics for bomber aircraft.

Table 14. Summary Statistics- Bombers

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	3	0	1	1	2	0	3	3	0	0	1	0
Bound Selected	15%	10%	20%	20%	15%	20%	15%	20%	15%	10%	20%	20%
Stable-30												
Mean	6.45%	4.83%	10.59%	14.34%	10.22%	12.77%	7.11%	16.60%	7.27%	5.02%	10.48%	14.96%
Std Dev	5.33%	3.40%	6.65%	20.78%	9.70%	12.88%	5.39%	12.96%	5.61%	3.88%	6.85%	20.34%
Median	5.07%	3.95%	10.12%	8.31%	8.94%	9.70%	5.86%	14.76%	5.97%	3.95%	10.65%	10.24%
% Stable to 30	88.89%	93.33%	93.10%	82.76%	85.71%	80.00%	92.59%	85.19%	86.67%	86.67%	93.10%	83.33%

Fighter & Attack

The Fighter & Attack category has data from years 1 to 37 and includes 1 to 11 programs in the calculations of means. The data is naturally truncated at 37 years which allows for 7 years of data to check for aging. Table 15 shows the summary statistics for fighter & attack aircraft.

Table 15. Summary Statistics-Fighter & Attack

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	6	4	3	3	2	0	2	2	2	3	0	1
Bound Selected	10%	15%	15%	20%	15%	20%	15%	20%	10%	15%	15%	20%
Stable-30												
Mean	8.11%	7.20%	10.41%	16.64%	11.11%	15.05%	8.08%	19.81%	7.42%	6.88%	8.33%	16.15%
Std Dev	3.16%	4.76%	5.16%	10.92%	9.37%	19.17%	4.56%	14.89%	2.93%	4.61%	4.41%	11.01%
Median	8.56%	5.99%	10.14%	14.01%	8.96%	8.97%	7.79%	15.50%	6.94%	5.39%	8.07%	14.36%
% Stable to 30	83.33%	96.15%	81.48%	74.07%	82.14%	80.00%	92.86%	67.86%	82.14%	92.59%	93.33%	75.86%
30-37												
Mean	19.49%	15.69%	17.54%	23.67%	10.82%	12.03%	6.99%	19.14%	12.09%	6.53%	11.84%	19.93%
Std Dev	7.27%	9.71%	9.04%	7.43%	7.60%	9.45%	2.73%	12.51%	4.87%	3.79%	5.71%	10.70%
Median	15.49%	14.52%	15.79%	25.19%	8.29%	10.70%	7.16%	13.60%	12.49%	5.24%	11.87%	21.71%
% Stable to 37	64.52%	87.88%	73.53%	64.71%	82.86%	81.08%	94.29%	68.57%	71.43%	100.00%	91.89%	69.44%

Helicopters

There is no determination for the point of stability for the first 10 years because data starts at year 11. Calculations for helicopters use 1 to 2 programs for means and the descriptive statistics only summarize from years 11 to 30 for all cost combinations. Percent stable calculations are also calculated from 11 to 30 years and 11 to 40 years and shown in table 16.

Table 16. Summary Statistics-Helicopters

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	10	10	10	10	10	10	10	10	10	10	10	10
Bound Selected	15%	15%	20%	20%	15%	15%	20%	20%	15%	15%	20%	20%
Stable-30												
Mean	9.60%	8.03%	17.07%	18.92%	8.90%	8.48%	17.18%	18.77%	9.55%	8.51%	16.85%	18.65%
Std Dev	6.98%	7.02%	14.54%	17.33%	8.26%	6.28%	14.64%	19.29%	6.34%	6.40%	16.06%	17.00%
Median	7.75%	5.33%	11.38%	15.70%	6.42%	7.31%	13.33%	13.97%	7.77%	6.46%	11.01%	16.24%
% Stable to 30	85.00%	85.00%	70.00%	75.00%	85.00%	85.00%	80.00%	60.00%	85.00%	80.00%	75.00%	70.00%
30-40												
Mean	7.20%	11.89%	22.03%	11.71%	9.00%	14.82%	23.64%	13.48%	10.69%	15.74%	24.75%	13.54%
Std Dev	6.40%	12.09%	13.32%	11.18%	8.98%	12.86%	14.09%	11.45%	8.47%	12.99%	15.49%	12.55%
Median	5.47%	5.55%	25.15%	9.43%	4.87%	10.70%	27.42%	11.54%	7.34%	11.07%	29.02%	8.51%
% Stable to 40	86.67%	80.00%	60.00%	76.67%	80.00%	76.67%	63.33%	66.67%	80.00%	73.33%	63.33%	73.33%

Reconnaissance

No data point is available for year 1 and it is assumed to be unstable at that point. Calculations of the means include from 1 to 3 aircraft. The data also stops at 39 years which allows for 9 years of aging. Table 17 summarizes the results.

Table 17. Summary Statistics-Reconnaissance

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	1	8	3	1	3	4	2	1	3	5	2	2
Bound Selected	20%	10%	20%	20%	20%	15%	15%	20%	15%	10%	20%	20%
Stable-30												
Mean	10.18%	5.24%	18.20%	16.89%	11.54%	11.54%	14.25%	17.17%	8.55%	6.21%	16.85%	14.11%
Std Dev	8.09%	4.82%	17.72%	10.57%	8.05%	7.44%	19.72%	11.57%	6.84%	3.80%	18.69%	9.84%
Median	7.10%	5.42%	12.97%	13.25%	9.53%	11.05%	9.46%	14.37%	6.94%	4.93%	12.02%	11.71%
% Stable to 30	82.80%	90.91%	70.37%	65.52%	85.19%	88.46%	82.14%	79.31%	88.89%	84.00%	75.00%	75.00%
30-39												
Mean	7.86%	7.54%	12.43%	14.15%	9.26%	13.94%	4.88%	14.91%	5.90%	3.41%	12.50%	15.52%
Std Dev	6.84%	5.93%	13.14%	7.82%	8.14%	5.90%	2.86%	13.94%	4.83%	2.48%	9.31%	6.99%
Median	5.19%	7.98%	6.51%	14.52%	5.64%	13.68%	4.58%	6.82%	5.19%	3.09%	14.87%	14.52%
% Stable to 39	84.21%	87.10%	72.22%	68.42%	86.11%	80.00%	86.49%	78.95%	88.89%	88.24%	75.68%	72.97%

Special Duty

Data stops at 33 years so analysis is truncated to 30 years. There are 2 to 4 programs used in the calculations of the means. No aging effects are able to be analyzed. Table 18 summarizes the results.

Table 18. Summary Statistics-Special Duty

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	3	1	3	2	1	1	3	2	0	0	0	0
Bound Selected	15%	15%	20%	20%	20%	20%	20%	20%	20%	15%	20%	20%
Stable-30												
Mean	12.26%	11.51%	19.41%	23.90%	13.18%	15.00%	15.31%	23.36%	11.26%	9.25%	19.58%	31.40%
Std Dev	10.91%	12.40%	19.05%	20.20%	6.91%	9.75%	10.26%	20.86%	7.67%	6.93%	19.27%	45.67%
Median	8.92%	8.36%	13.96%	19.38%	11.14%	12.98%	12.43%	19.36%	10.00%	8.29%	13.90%	20.30%
% Stable to 30	81.48%	86.21%	74.07%	53.57%	82.76%	79.31%	70.31%	53.57%	90.00%	90.00%	73.33%	50.00%

Training

Data goes from years 1 to 24 and 35 to 55. We truncate at 24 years from IOC and the latter part is not analyzed for aging. Training includes 1 to 2 aircraft and is summarized in table 19.

Table 19. Summary Statistics-Training

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	8	9	6	2	1	1	2	1	1	0	2	0
Bound Selected	10%	10%	15%	20%	15%	20%	15%	20%	10%	20%	15%	20%
Stable-24												
Mean	6.36%	11.83%	9.82%	21.40%	8.49%	14.21%	8.41%	21.76%	7.09%	13.92%	9.84%	19.56%
Std Dev	5.49%	12.96%	8.04%	19.38%	6.52%	14.32%	6.32%	20.07%	5.44%	15.45%	6.39%	18.62%
Median	5.70%	7.49%	8.51%	16.47%	7.51%	8.23%	7.43%	13.95%	5.85%	7.54%	8.37%	14.21%
% Stable to 24	87.50%	80.00%	83.33%	68.18%	86.96%	78.26%	86.36%	65.22%	82.61%	79.17%	81.82%	70.83%

Transport & Tanker

Transport & Tankers have enough data points to check the stability point to 30 years from IOC as well as from years 30 to 40. This is the only aircraft type that does not need any extra assumptions or truncations. Mean calculations include data from 2 to 4 programs and summary statistics are found in table 20.

Table 20. Summary Statistics-Transport & Tanker

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	11	4	2	5	2	1	2	6	5	1	1	5
Bound Selected	15%	20%	20%	20%	15%	20%	15%	20%	10%	15%	20%	20%
Stable-30												
Mean	8.69%	14.40%	15.63%	19.24%	9.16%	12.43%	9.00%	19.32%	7.17%	8.43%	11.91%	16.22%
Std Dev	6.66%	9.24%	10.49%	18.08%	4.74%	6.71%	5.40%	15.29%	4.26%	6.02%	5.66%	12.69%
Median	7.50%	11.51%	13.72%	12.25%	8.24%	11.12%	7.86%	15.55%	6.68%	7.97%	10.98%	13.20%
% Stable to 30	94.74%	76.92%	78.57%	76.00%	96.43%	93.10%	92.86%	70.83%	84.00%	93.10%	86.21%	68.00%
30-40												
Mean	11.89%	8.98%	16.16%	15.79%	8.50%	13.73%	6.40%	15.44%	6.94%	5.99%	11.70%	12.06%
Std Dev	4.90%	3.44%	3.79%	8.28%	2.63%	5.63%	3.10%	7.02%	2.54%	4.94%	5.47%	4.86%
Median	10.57%	8.20%	14.91%	13.58%	8.31%	13.22%	5.84%	13.55%	7.32%	3.79%	9.90%	12.88%
% Stable to 40	89.66%	83.33%	76.32%	74.29%	97.37%	92.31%	94.74%	70.59%	85.71%	92.31%	87.18%	77.14%

Unmanned Aerial Vehicle (UAV)

There are only three programs in this aircraft type and it contains data from years 1-11 for 1 to 3 programs. No aging affects are able to be analyzed yet for UAVs because they are so new relative to other aircraft types. Summary statistics are shown in table 21.

Table 21. Summary Statistics-Unmanned Aerial Vehicle (UAV)

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	5	5	3	8	5	4	6	5	5	4	6	5
Bound Selected	20%	20%	20%	15%	15%	20%	20%	15%	15%	20%	20%	15%
Stable-11												
Mean	17.17%	17.40%	28.57%	18.23%	10.69%	15.82%	28.66%	11.18%	12.55%	15.26%	23.11%	13.87%
Std Dev	6.57%	6.75%	19.12%	17.12%	6.85%	7.01%	17.57%	6.94%	5.08%	4.55%	8.56%	11.00%
Median	17.55%	17.93%	24.19%	12.91%	10.06%	17.88%	18.75%	9.47%	12.02%	16.30%	18.23%	11.57%
% Stable to 11	66.67%	50.00%	37.50%	66.67%	83.33%	71.43%	60.00%	83.33%	83.33%	71.43%	60.00%	83.33%

Aircraft Type Summary

The research compares stability by aircraft type with the assumption that the descriptive data displayed is an accurate representation of the aircraft type at large. There are limitations with sample sizes but still significant findings. We focus this analysis by looking at underlying trends and further investigate where necessary. The first is that the CPFH metric is the most unstable for 5 of the 8 aircraft types. Helicopters, which exhibit minor differences in cost types, are a special case for this research because data doesn't start until 11 years from IOC. Also, the general differences between rotary aircraft and fixed wing aircraft are greater than the differences within fixed wing aircraft types.

Cost per TAI was the best metric in the aggregate analysis, with stability demonstrated at the 10% bound, a trend that appears the same across platform type. For this reason, the research hones in on cost per TAI as a basis of comparison. Aside from helicopters, which is hard determine the point of stability, all aircraft types exhibit some form of stability at 0 to 5 years from IOC which also allows them to be compared. Looking at Table 22, there are potentially 2 or 3 distinct groupings for the means of percent differences after stability occurs. Bombers, Fighter/Attack, Training, and Transport/Tanker all have total CPTAI means around 7% and medians from 5% to 7%.

Reconnaissance and helicopters are at 8.55% and 9.55% respectively with medians around 7%. Special duty aircraft and UAVs seem to be different from the rest in the total CPTAI category by with means around 11% to 12% and medians of 10% to 12%. Another notable trend not shown in Table 5 is that trainers are less stable in CES 1 (manpower) with a mean around 14% while the other aircraft types are below 10%. This makes sense due to the rotating number of pilots going through pilot training. Also, special duty aircraft exhibit more variance in CES 3 (maintenance). The special duty aircraft in this research are all C-130 variants that are being used for special operations missions, which may lead to more stress on the aircraft.

Table 22. Total Cost per TAI Summary Statistics (Stable to 30 years from IOC) by Aircraft Type

Aircraft Type	Years to stability	Best Bound	Mean	Standard Deviation	Median
Training	1	10%	7.09%	5.44%	5.85%
Transport/ Tanker	5	10%	7.17%	4.26%	6.68%
Bombers*	0	15%	7.27%	5.61%	5.97%
Fighter/ Attack	2	10%	7.42%	2.93%	6.94%
Reconnaissance	3	15%	8.55%	6.84%	6.94%
Helicopters	10	15%	9.55%	6.34%	7.77%
Special Duty**	0	20%	11.26%	7.67%	10.00%
UAV	5	15%	12.55%	5.08%	12.02%

* When tested to a 10% bound, Bombers had 70.00% stability

** When tested to 15% bound, Special Duty had 76.67% stability

Stability Recap

Using the means of percent differences for each year from IOC allows the research to identify O&S stability properties of aircraft at the top level as well as by aircraft type. Cost per TAI is the cost type that exhibits the tightest stability and steered the analysis for stability properties by aircraft type. Though there are no inferential statistics, the descriptive statistics provided will be helpful for cost estimators in the future.

Part 2. Predicting O&S Costs Using Multiple Regression

Developing a model using multiple regression is an iterative process and is made more robust with certain validating assumptions. If at any point one of the validating assumptions is failed, corrective action is taken, and the process is started over. The validating tests used in this analysis include Holm-Bonferroni Correction, Variance Inflation Factors, Cook's Distance Test, Shapiro-Wilk Tests, and Breusch-Pagan Tests. Possible remedies for failure of any of these tests include removal of a variable, removal of data points, or natural log transformations.

Response Variable

The regression model predicts the total operating cost per total aircraft in the inventory (total cost per TAI) as an output variable.

Predictor Variables

The following independent variables are the predictor variables included in the preliminary model. Variables for "Years from IOC" and "Stable vs. Unstable" are created using the results from the stability portion of this research while all other variables are obtained directly from the AFTOC database. Through the iterative process of model building some variables are removed for failing diagnostics.

- Unit Cost *(Continuous Variable):* This is the unit cost of the aircraft for the program
- Tempo *(Continuous Variable):* Tempo is calculated according to the RAND model described in Chapter III and is the total flight hours in a year divided by the TAI.
- Average Age *(Continuous Variable):* This variable is the average age of all aircraft in the program at the end of the year. The RAND model divides this number by 100 but our research does not.
- Location of Lead Logistics Center *(Binary Variables):* These variables are the location of the lead air logistics center (ALC). The base case is Ogden Logistics

Center (OO-ALC). Binary variables are created for Warner Robins Air Logistics Center (WR-ALC), Aeronautical Systems Center (ASC) which is now Life Cycle Management Center, and Oklahoma City Logistics Center (OC-ALC).

- Contract vs. Organic Logistics Support *(Binary Variables):* These variables describe if the program is currently being maintained by contract logistic support (CLS) or organic logistics support.
- Mission Type *(Binary Variables):* The mission types explored are the eight from the stability portion of research and include Bombers, Fighter/Attack, Helicopters, Reconnaissance, Special Duty, Training, Transport/Tanker, and UAV. The base case in the research is Transport/Tanker.
- Years from IOC *(Binary Variables):* These variables include years 1 through 30 from IOC to see if any specific years may be significant.
- Stable vs. Unstable *(Binary Variables):* These variable is derived from the stability portion of research and indicates whether the program is considered stable or not. Stability starts after 5 years from IOC and coincides with the stability point for cost per TAI, which is where cost per TAI is stable 80% of the time at a 10% bound.

Validation Pool

Randomly selecting 80% of the 609 data points to create the model and 20% to test resulted in 484 (79.47%) data points for the model and 125 (20.53%) data points for test. Once the initial model passes all validating assumptions, the final output regression equation is used with the 125 test data points to get predicted values.

Stepwise Regression and Diagnostics

After all predictor variables are put into the 80% model, the stepwise function is used. Recall from Chapter III that the research uses the stepwise mixed function in JMP Pro® with a p-value of 0.05 to enter as well as exit the model. The preliminary model output that passes all diagnostics is shown in Figure 7.

Summary of Fit

RSquare	0.87482
RSquare Adj	0.871358
Root Mean Square Error	0.309846
Mean of Response	15.88214
Observations (or Sum Wgts)	484

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	315.33562	24.2566	252.6610
Error	470	45.12211	0.0960	Prob > F
C. Total	483	360.45772		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	VIF
Intercept	4.5742813	0.388341	11.78	<.0001*	.
LN Tempo	0.645439	0.042804	15.08	<.0001*	2.8731921
LN Unit Cost	0.3826314	0.014446	26.49	<.0001*	1.9404917
Avg_Age	0.0169727	0.001758	9.66	<.0001*	1.9816567
Stable	-0.144654	0.051259	-2.82	0.0050*	1.4179116
Y WR-ALC	0.5619685	0.061604	9.12	<.0001*	4.7749103
Y ASC	0.4589005	0.074979	6.12	<.0001*	3.8710368
Y OC-ALC	0.3299546	0.066501	4.96	<.0001*	4.4430619
Y Fighter	0.4005612	0.061328	6.53	<.0001*	3.930935
Y Bomber	0.6527733	0.08064	8.09	<.0001*	2.9829822
Y Special	0.3597896	0.047994	7.50	<.0001*	1.5860347
Y Recon	0.6283371	0.066885	9.39	<.0001*	1.7872676
Y Helo	0.4041136	0.087315	4.63	<.0001*	1.3762486
Y Trainer	-0.81709	0.088325	-9.25	<.0001*	1.8535361

Figure 7. Preliminary Model that Passes all Diagnostics

Holm-Bonferroni Correction

The first diagnostic applied to the model is the Holm-Bonferroni Correction which is a measure to reduce type I error. This is done by lowering the p-value to reject the null hypothesis by dividing the alpha (α) level by the number of predictor variables used in the model. For this analysis, an α of 0.05 is used with 13 predictor variables. Applying the Holm-Bonferroni correction results in $\alpha = 0.05/13 = 0.003846$. Only the stability variable is over this threshold at 0.005 however this is a conservative measure the variable is kept in the model.

Variance Inflation Factor

The Variance Inflation Factor (VIF) is used to detect if multicollinearity is present in the model. Traditionally, a VIF value above 10 is considered to have collinearity with another variable and should be removed or investigated to find which variables are collinear. Shown in Figure 8, all VIF values are below 10 with the highest being 4.77, a binary variable for Warner-Robbins as the lead logistics center for an aircraft.

Cook's Distance Test

The finalized preliminary model needs to have data points that are not overly influential to the overall model. A Cook's Distance Test checks for this measure and considers any point to have a value of over 0.5 to be influential to the model. The preliminary model had one data point with a Cook's Distance of 0.438 shown in Figure 8. While this is still under the threshold, analysis of the studentized residuals revealed that the data point is 6.69 standard deviations away from the mean. The data point in question was the O&S costs of RQ-4B Global Hawk in its first year from IOC. With this data point's temporary removal and re-running regression, the dummy variable for UAV was no longer significant in the model. This results in removal of the UAV predictor variable from the model, however the point remains.

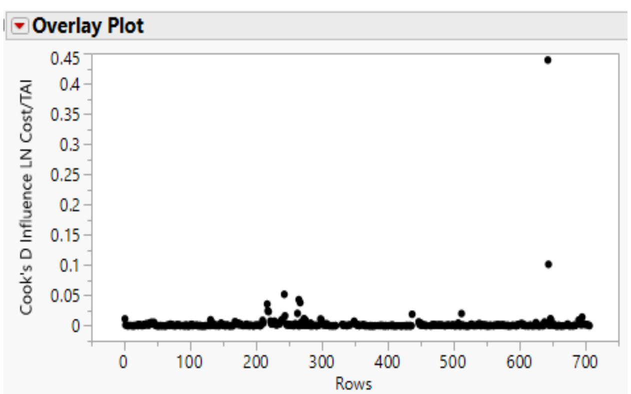
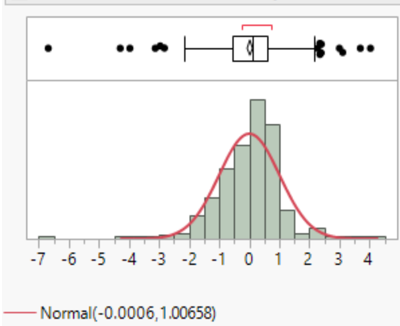


Figure 8. Display of Cook's Distance Plot

Studentized Residuals

The next check is testing the assumption that residual values are normally distributed. To complete this, we create a histogram of the studentized residuals and conduct a Shapiro-Wilks (S-W) test for normality. A histogram of the studentized residuals as well as S-W test is shown in Figure 9. A normal distribution contains 95% of the data within 2 standard deviations and 99.7% of the data within 3 standard deviations. The residuals of our preliminary model are distributed such that 95.25% of the data is within 2 standard deviations and 98.55% of the data is within 3 standard deviations. While not exact, it is close to what is expected from a normal distribution.

Figure 9 also shows the S-W test, which the model's residuals failed statistically. This means that statistically the curve cannot be considered a normal distribution. However, looking at the shape of the distribution, the residuals follow the bell shape curve characteristic of a normal distribution. The exception is that there are more values centered around zero than a normal distribution which makes this a soft fail of the test. Values centered around zero are acceptable whereas large spikes on the histogram tails would be troublesome.



Summary Statistics

Mean	-0.000623
Std Dev	1.0065846
Std Err Mean	0.0457538
Upper 95% Mean	0.089278
Lower 95% Mean	-0.090524
N	484

Fitted Normal

Parameter Estimates

Type	Parameter	Estimate	Lower 95%	Upper 95%
Location	μ	-0.000623	-0.090524	0.089278
Dispersion	σ	1.0065846	0.9469166	1.0743391

-2log(Likelihood) = 1378.88551698443

Goodness-of-Fit Test

Shapiro-Wilk W Test

W	Prob<W
0.937813	<.0001*

Note: Ho = The data is from the Normal distribution. Small p-values reject Ho.

Figure 9: Studentized Residuals and Shapiro-Wilk Test

Breusch-Pagan

The final validation criteria that the model must pass is the Breusch-Pagan test against heteroscedasticity. Heteroscedasticity is the property of having non-constant variance throughout the range of predicted values. Testing for constant variance requires the number of observations (N), degrees of freedom of the model, sum of squared errors (SSE), and sum of squared residuals (SSR). Figure 10 shows the p-value of the B-P test with the required values. A low p-value in a Breusch-Pagan test rejects the null hypothesis that constant variance is exhibited in the model. Figure 11 shows the residuals by predicted values.

Breusch-Pagan Test

N	484
df(Exp)	13
SSE	45.122
SSR	6.391

T.S.	**367.6655**
Pvalue	**1.48E-70**

Figure 10. Breuch-Pagan Test for Constant Variance

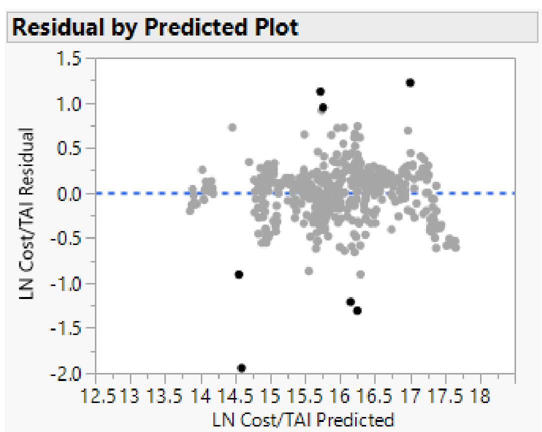


Figure 11. Residual by Predicted Values Plot

Initially, heteroscedasticity was more prevalent and in an effort to reduce this we transform the data by applying natural log transformations. The dependent variable, Cost per TAI is transformed as well as the independent variables for unit cost and tempo. After these transformations, the p-value of the test statistic is still almost zero, however the residual by predicted plot does not appear to have any trend. A model does not have constant variance if the residual values are close to zero on one end of the predicted values and far from zero on another end, appearing cone shaped. It is also important to note that the 7 data points that were outside 3 standard deviations are highlighted in figure 11 and show again that the issue is arising at the tails and not the middle. Like S-W, the test for constant variance is failed but without a distinguishable trend in the residual by predicted plot and with the failure being caused by outliers, we consider this to be a soft fail.

Validation of the Model

Once the preliminary model passes all diagnostic tests and assumptions we must use the 20% validation to validate that the model for accuracy. Validation of the model involves comparing the Mean Absolute Percent Error (MAPE) and Median Absolute Percent Error (MdAPE) of the 80% preliminary model to the 20% validation pool. Figure 12 includes a histogram and summary statistics for Absolute Percent Error (APE) of the 80% preliminary model. The MAPE is 1.41% and MdAPE is 1.09% which are both very close to zero. Figure 13 is a histogram and summary statistics for APE of the 20% validation pool. The MAPE for the 20% validation pool is 1.37% and the MdAPE is 1.03% which is also very close to zero.

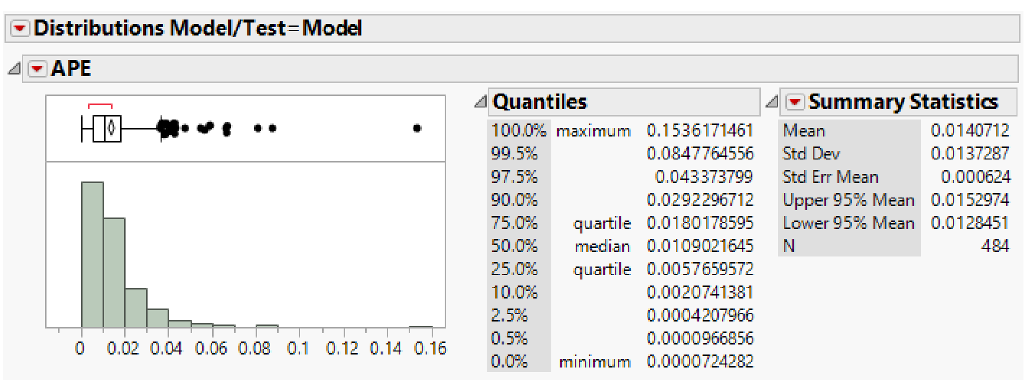


Figure 12. Summary Statistics of Absolute Percent Error (APE) for 80% Model

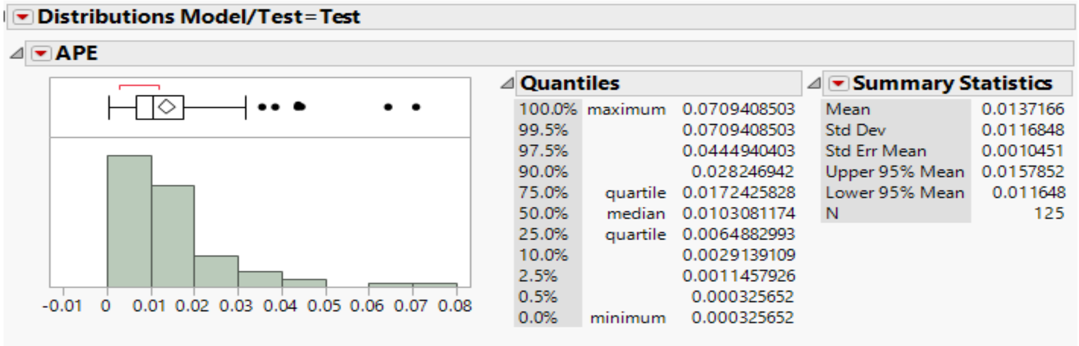


Figure 13. Summary Statistics of Absolute Percent Error (APE) for 20% Validation Pool

In addition to comparing MAPE and MdAPE, we also compare the R^2 and adjusted R^2 values of bivariate actual vs. predicted plots for both the 80% model and the 20% validation pool. Figure 14 is the bivariate plot for the 80% model and has an R^2 of 0.875 and adjusted R^2 of 0.875. Figure 15 is the bivariate plot for the validation pool and has an R^2 of 0.872 and adjusted R^2 of 0.871. A comparison of the two plots show that the values are very close to each other.

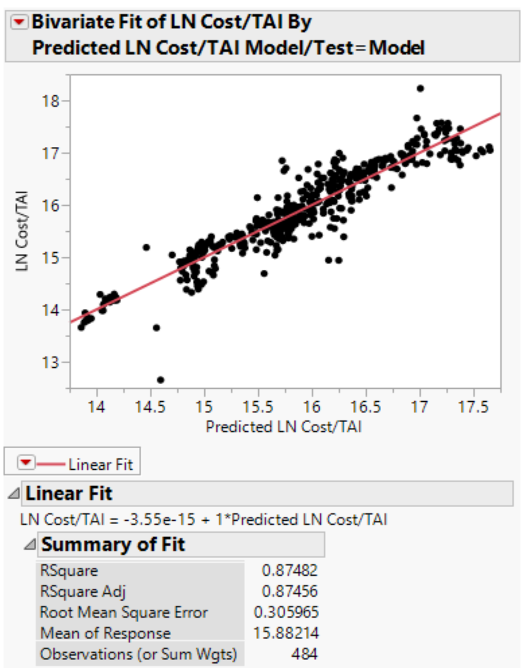


Figure 14. Bivariate Plot of Actual vs. Predicted for 80% Model

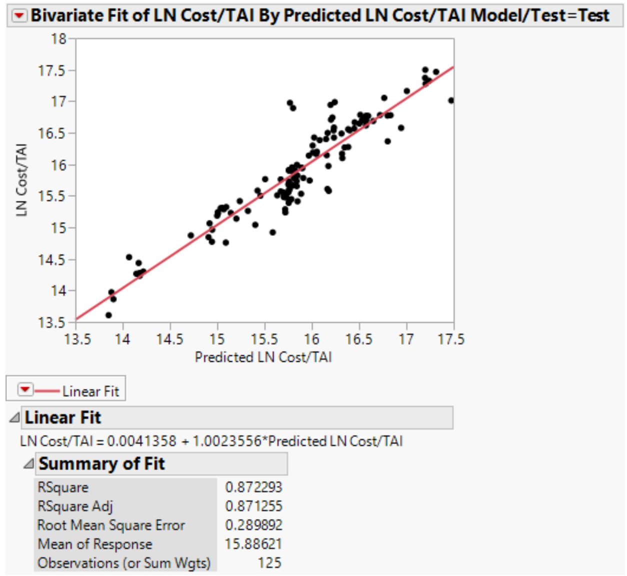


Figure 15. Bivariate Plot of Actual vs. Predicted for Validation Pool

The close comparisons of MAPE, MdAPE, and bivariate plots allow us to conclude that the 80% model is valid compared to the 20% validation pool. From this point we move forward and develop the final model.

Final Multiple Regression Model

Now that all model assumptions and diagnostics are passed and the model is considered valid compared to the 20% validation pool the final model is created. The final model includes all data points and uses the same predictor variables as the preliminary model and is shown in Figure 16. While 10 is the cut off value for VIF scores for multicollinearity, the research team dived further into high VIFs and potential interactions between the variables. The logistics centers had the highest VIFs and were temporarily removed which caused two binary variables to become less significant, Stability variable (p-value = 0.0155) and Y Fighter (0.0428). While still significant with an alpha of 0.05 the two would then fail the Bonferroni-Holm correction and indicated that they both have interactions with logistics centers. Adding centers back into the model one at a time revealed that there are significant interactions between Y Fighter and Y WR-ALC (p-value < 0.0001) and a moderately significant interaction between the stability variable and Y ASC (0.00259). These interactions are not captured in the final model but may affect results of the regression model. It is also important to note that the model does not show binary variables for Transport/Tanker (Y Transport) or UAV (Y UAV). This is because the base case is Transport/Tanker and the UAV variable was not significant in the model. When using the model an estimator would treat a Transport/Tanker aircraft the same as UAVs and have no input into the model. The same is true for the binary variable for Ogden Logistics Center (Y OO-ALC) because it is the base case.

Summary of Fit

RSquare	0.875153
RSquare Adj	0.872426
Root Mean Square Error	0.304331
Mean of Response	15.88298
Observations (or Sum Wgts)	609

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	13	386.29212	29.7148	320.8344
Error	595	55.10722	0.0926	Prob > F
C. Total	608	441.39934		<.0001*

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|	Std Beta	VIF
Intercept	5.0409673	0.342326	14.73	<.0001*	0	.
LN Tempo	0.6057234	0.038346	15.80	<.0001*	0.390638	2.9145461
LN Unit Cost	0.3759254	0.012697	29.61	<.0001*	0.584831	1.8595895
Avg_Age	0.0159862	0.001556	10.27	<.0001*	0.206921	1.9335239
Stable	-0.156601	0.044865	-3.49	0.0005*	-0.05975	1.3963774
Y WR-ALC	0.5078126	0.05373	9.45	<.0001*	0.29823	4.7454278
Y ASC	0.3889743	0.067415	5.77	<.0001*	0.165783	3.9344693
Y OC-ALC	0.3082739	0.059011	5.22	<.0001*	0.159366	4.4353447
Y Fighter	0.3130843	0.052642	5.95	<.0001*	0.170381	3.9113466
Y Bomber	0.5984688	0.07058	8.48	<.0001*	0.20149	2.6910904
Y Special	0.3489009	0.042398	8.23	<.0001*	0.149968	1.5827891
Y Recon	0.6497474	0.054053	12.02	<.0001*	0.220535	1.604157
Y Helo	0.3443836	0.08192	4.20	<.0001*	0.070327	1.3337481
Y Trainer	-0.836586	0.077582	-10.78	<.0001*	-0.21925	1.9703146

Figure 16. Final Regression Model

Regression Recap

This portion of analysis started with the original RAND regression model and added programmatic information from AFTOC. Using results from the stability section of thesis and AFTOC programmatic information we were able to create variables to predict total O&S costs per TAI. In the iterative process of model building there are a variety of diagnostics that must be met in multiple regressions before it can be considered a viable model. All diagnostics were met and the model set was tested against the test set with minimal difference in results. The final model is able to explain 87.24% of the variance in the data set. Due to natural log transformation of variables, once transformed back from log space, the output is median cost per TAI rather than mean cost per TAI.

Chapter Summary

This chapter presents the results from both the stability properties analysis as well as the final multiple regression model. Discussed first are stability properties and results for the WSER. Then we dive into the stability properties for the year to year metric and different CESs. After a top-level analysis, we compare by aircraft type. Finally, we discuss the results from the multiple regression model that uses data from AFTOC and a variable derived from the stability portion. Chapter 5 of this thesis highlights the major findings for each question. In addition, limitations of the research are pointed out and any recommendations for future research.

V. Conclusions and Recommendations

Chapter Overview

The purpose of this chapter is to provide final conclusions made from all analyses, limitations, and suggestions for future research. Major findings for the stability portion include determining how many years from IOC stability occurs and to what degree a program remains stable. There are significant findings for both the WSER metric as well as the year to year metric. In addition, a statistically significant multiple regression model was developed to accurately predict total O&S costs per TAI. First, we revisit the four research questions that were initially proposed in Chapter 1 and discuss the significant findings for each question. Then, we highlight the limitations of our research and identify areas for future research to continue.

Research Questions Answered

#1: Using the Weapon System Enterprise Review (WSER) 15% threshold for reporting as a baseline, what is the more accurate, data driven threshold for stability?

Question one is the original purpose of this research and basis for the subsequent research questions. The first finding in the best bound analysis is that only 3 of the 9 WSER and cost combinations analyzed have 80% stability to 30 years from IOC at the 15% bound. Therefore, we do not recommend the 15% blanket bound as it is not a good metric for all categories. For the total O&S cost type, stability is first attained around 8 to 9 years and only WSER 2 (Other Logistics Costs) used 15% as its best bound. CPFH uses the 20% threshold as the best bound for all three of the WSER categories. In comparison to total O&S costs, CPFH reaches stability earlier than total O&S costs but does have higher means and medians. CPTAI has the tightest bounds between all three WSER categories with 2 of the 3 combinations using the 15% bound.

In regards to the most stable WSER category regardless of cost type it is WSER 2. WSER 1 (CAM) is the least stable cost type and uses the 20% bound, of which only 1 stays stable more the 80% of the time. Overall, WSER 1 is worst for stability and it is recommended to use 20% as the bound. The most stable combination of the 9 is CPTAI WSER 2 where it is 87.5% stable at a 15% bound and has a mean and median of 11.58% and 11.78% respectively. For aging, 6 out of 9 of the WSER combinations have higher means and medians in the 30-40 year from IOC range. Most aging appears to be in WSER 3 (Other O&S Costs). Table 23 summarizes the recommended bound for each selection as well as descriptive statistics to further explain characteristics.

Table 23. WSER Years to Stability and Bound Recommendation

	WSER 1	WSER 2	WSER 3	CPFH WSER 1*	CPFH WSER 2	CPFH WSER 3	CPTAI WSER 1**	CPTAI WSER 2	CPTAI WSER 3
Stable After (Years)	9	9	8	6	3	3	5	6	5
Recommended Bound	20%	15%	20%	20%	20%	20%	20%	15%	15%
Mean	17.77%	12.59%	14.59%	18.67%	15.88%	15.64%	17.44%	11.58%	13.43%
Std Dev	6.62%	2.63%	4.90%	6.43%	4.35%	5.84%	5.71%	2.83%	4.58%
Median	16.91%	12.39%	13.74%	18.78%	14.49%	14.39%	16.41%	11.78%	12.58%

*CPFH WSER 1 is only stable 62.50% of the time once 20% bound is reached

**CPTAI WSER 1 is only stable 76.00% of the time once the 20% bound is reached

#2: When can O&S costs of a program be considered stable?

While question one aims to provide a data driven number for the WSER, question two aims to determine stability for the year to year metric as well as the appropriate percent bound. The first major finding is that when looking at the five Cost Element Structures (CES), only the first three display stability properties. CES 4 and 5 do not display stability at the aggregate level and were not analyzed further. It is important to note that this is a reasonable approach because the first three categories make up around 80% of all total O&S costs (O'Hanlon, 2018).

For bounds testing by cost type, CPFH has the highest bounds, followed by total costs and then CPTAI. This is consistent with the WSER results which further reinforces the finding. The tightest bounded cost type is CPTAI which got down to the 10% bound in two of its three categories. The overall best recommended metric for stability is CPTAI CES 1 which is manpower. This is likely the most stable because it is the manpower needed per aircraft and it is easy to predict the number of people assigned to an aircraft. CPTAI total is also a good metric, is stable 80% of the time to 30 years from IOC, and reaches stability after 5 years from IOC. Total cost includes CESs 4, 5, and 6 and while it is hard to determine stability for them individually, we can predict some sort of stability with all six CESs combined. The CPTAI total O&S costs is also the metric used for the stability variable in the regression portion of the research. Table 24 summarizes when costs can be considered stable, to what degree, and the percent of time it falls within the bound up to 30 years from IOC.

Table 24. Year to Year Time to Stability

	O&S Total	CES 1	CES 2	CES 3	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3
Stable After (Years)	5	7	9	5	3	3	2	8	5	8	6	5
Bound Selected	15%	15%	15%	20%	15%	20%	20%	20%	10%	10%	15%	20%
Mean	10.24%	9.75%	13.27%	18.30%	11.44%	13.39%	12.42%	19.43%	8.44%	8.15%	12.63%	17.68%
% Stable to 30	92.00%	95.65%	85.71%	72.00%	85.19%	88.89%	85.71%	63.64%	80.00%	86.36%	83.33%	68.00%

#3: How do stability characteristics vary by aircraft platform type?

When looking at stability properties by platform type it is important to note that there are only comparisons of descriptive statistics. This is due to the small sample size caused by splitting the data up into the eight different aircraft categories. While values are compared, some have sample sizes of 1 or 2 while others are above 10 and could influence data. With that in mind, there are some notable trends that appear to exist between aircraft. We will talk about trends by cost type (total, CPTAI, CPFH), cost category (total, CES1, CES2, CES 3), and effects on aging aircraft.

The first trend in cost type is that the CPFH metric requires the highest bounds and has the highest mean and median values. For helicopters, all cost types are the same. Of the categories with stability differences in cost type, CPFH is the widest bound for 5 out of 7 aircraft types. Transport/Tanker and UAV are the two that don’t exhibit this trend and this could be due to the number of flying hours their mission types entail. CPTAI as a cost group exhibits the most stability which is also in line with findings from questions 1 and 2.

Notable trends for cost category include CES 3 having the most unstable bounds while total costs and CES 1 exhibit the most stability. Again, this coincides with the findings from question 2. For the eight aircraft types, only UAVs exhibited more stability in CES 3 than CES 1 or 2. This could be due to the fact that they are relatively newer aircraft or possibly because their missions don’t put as much stress on the aircraft compared to manned aircraft.

Aging effects are harder to determine because of the available data on each aircraft type. Aging can only be looked at on 4 of the 8 aircraft types because not all had data points for 30 years to 40 years from IOC. We consider a program to have aging affects if the program is more stable to its best bound from the stability point to 30 years than it is for 30 to 40 years. The four that were able to be checked for aging are Fighters/Attack, Helicopters, Reconnaissance, and Transport/Tankers. All but Reconnaissance demonstrate aging affects as it relates to stability.

Using the trends from cost type and cost category, the best overall metric to compare stability properties by aircraft type is total O&S cost per TAI. While it is not perfect, this combination exhibits stability to the tightest bound and allows us to distinguish any differences between the groups. Training, Transport/ Tanker, Bombers, and Fighter/ Attack exhibit the most stability, Reconnaissance and Helicopters exhibit moderate stability, and Helicopters and UAVs exhibit the least amount of stability. Table 25 illustrates how aircraft types compare for the total O&S cost per TAI metric.

Table 25. Total Cost per TAI Summary Statistics (Stable to 30 years from IOC) by Aircraft Type

Aircraft Type	Years to stability	Best Bound	Mean	Standard Deviation	Median
Training	1	10%	7.09%	5.44%	5.85%
Transport/ Tanker	5	10%	7.17%	4.26%	6.68%
Bombers*	0	15%	7.27%	5.61%	5.97%
Fighter/ Attack	2	10%	7.42%	2.93%	6.94%
Reconnaissance	3	15%	8.55%	6.84%	6.94%
Helicopters	10	15%	9.55%	6.34%	7.77%
Special Duty**	0	20%	11.26%	7.67%	10.00%
UAV	5	15%	12.55%	5.08%	12.02%

* When tested to a 10% bound, Bombers had 70.00% stability

** When tested to 15% bound, Special Duty had 76.67% stability

#4: Using multiple regression, how accurately can we predict O&S costs for a given year using explanatory variables?

The major finding for this question is that we are able to accurately predict O&S costs of a given aircraft based on time from IOC and other variables available from AFTOC. The final model is able to explain 87.24% of the variance in the data (Adjusted R^2) all while passing the diagnostics required for robust model building. CPTAI Total O&S costs is used for the stability variable in the model and was the second best overall metric in the stability portion only to CPTAI CES 1. Using CPTAI Total also aligns with the original regression model created by RAND. It is important to note that the dependent variable is the natural log of total cost per TAI. When actually using the model, the cost estimator must transform the output from log space to normal space and the value given would be a median rather than mean value. This model has value as a top level cross check or an initial basis for a rough order of magnitude (ROM) estimate early in a program's lifecycle.

The explanatory variables include natural log Tempo (Flight hours/TAI), natural log Unit Cost, Average Age of the aircraft in the fleet, Stability, Location of Lead Logistics Center, and aircraft platform type (technology). All individual variables are significant. Figure 17 displays the percentage at a grouped level of contribution to standard beta while Figure 18 displays the percentage that each individual predictor variable contributes. Aircraft type is the largest percent of standard beta with 36%, followed by Logistics Center (22%), and then Ln Unit Cost (20%). The smallest contributor to standard beta is Stability with 2%.

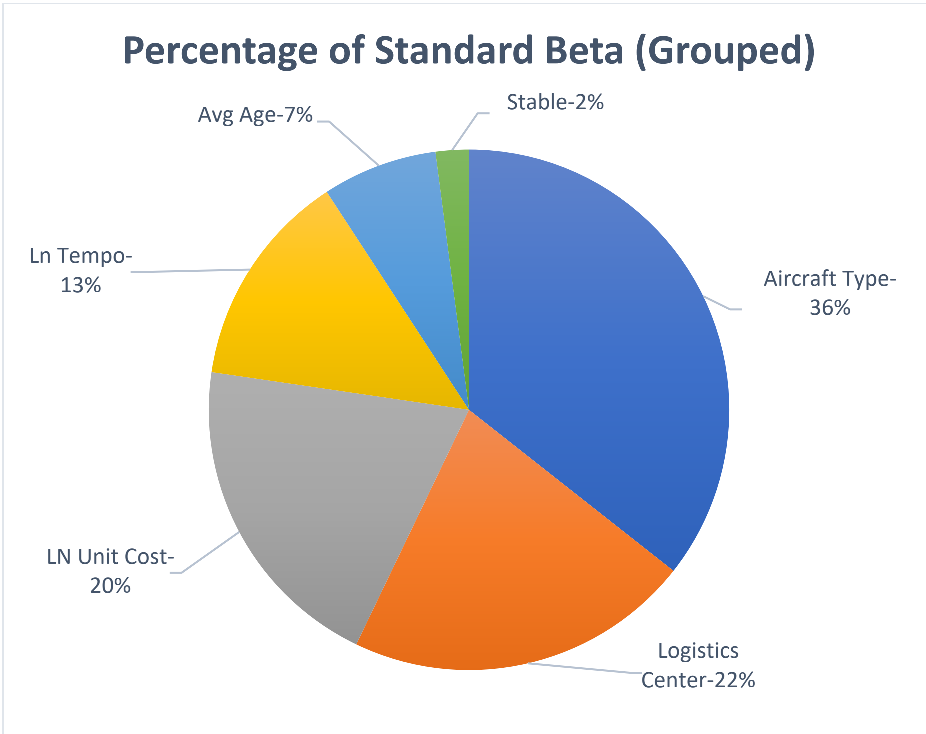


Figure 17. Percentage of Standard Beta Grouped by Variable Type

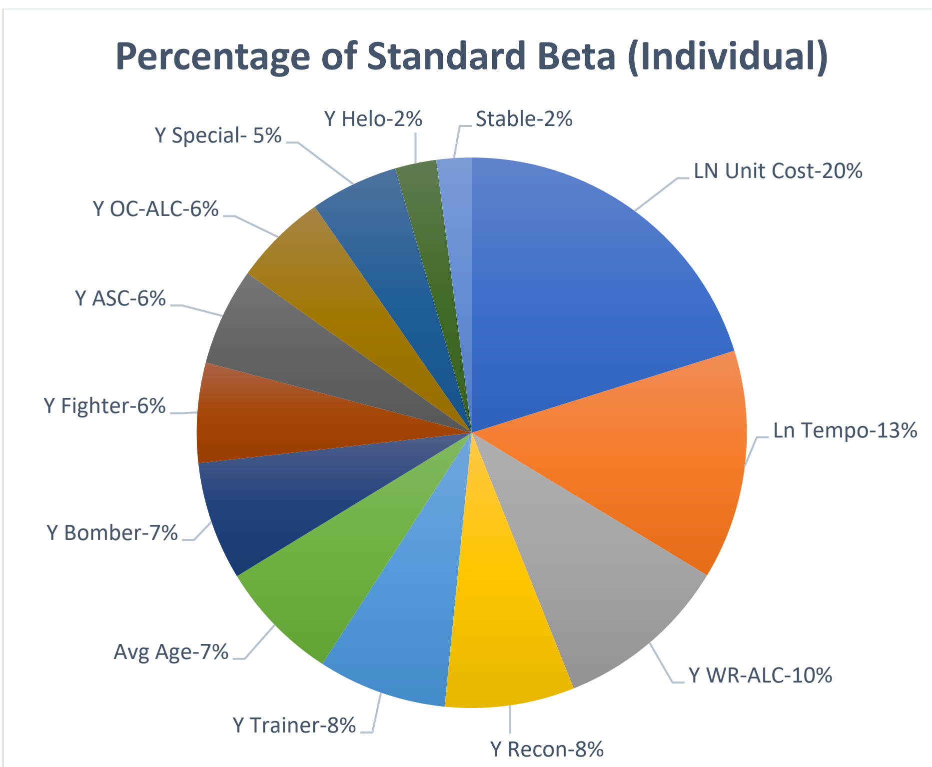


Figure 18. Percentage of Standard Beta by Individual Variable

Limitations

The largest limitation when trying to determine stability is that the research standardizes by years from IOC. In theory it is a reasonable way to standardize, but in reality, programs distinguish initial capability differently. Programs may declare IOC earlier than what it should be due to schedule or other pressures. Not every program declares IOC the same way but IOC is better than full rate production because they are already incurring O&S costs by that point. In some cases, the program incurs O&S for multiple years before declaring IOC which could also skew the data to show stability from IOC sooner than it should. Another point to be made with IOC dates is that the research team ignored the month that IOC was declared. It is assumed that if a program declared IOC in a year, its costs for one year from IOC would end on December 31 of the next year. However, this would skew the data at MOST one year if a program declared IOC in January. For simplicity, the year that program declares IOC is determined to be year zero. Again, this affects the stability portion more but also affects the stability variable used in the regression portion of analysis.

Another limitation in the stability portion is that when aggregating data by years from IOC the research team used the mean of percent differences. As noted in Chapter 3, means were chosen over do the median percent difference because it skews the data towards instability. We want to be as conservative as possible to counteract any other limitations of the research. Descriptive statistics using mean and median are provided but these descriptions are for the means of the aircraft for each year from IOC.

The scope of the research only including Air Force aircraft is another limitation. The data used comes from AFTOC which only provides Air Force aircraft, therefore it is possible that different services could exhibit different properties for aircraft. In addition, the methodology may not hold with other types of programs such as ship programs, space programs, or munitions programs. The same methodology however could be applied to these other types of programs to determine if stability properties exist.

In addition, the variable for tempo has flight hours in it. This variable relies on the ability to properly assess what the number of flight hours are going to be in a given year. There are some laws that restrict flight hours which can be helpful to the tempo variable but it still relies on a projection. Also, there is an assumption that the unit cost given in AFTOC is the true unit cost for a program. For newer programs that aim to use the model, unit cost may be another variable that is hard to distinguish because there may be a variety of factors that could change the final unit cost. The final variable that may be limited is the stability variable, which relies on the results from the first portion of this thesis to be derived. As discussed, there are limitations with the stability portion of research so the actual use of the stability variable may have inaccuracies. However, the stability variable contributes only 2% percent of standard beta so it is likely not troublesome.

Another limitation to the regression portion is that overhauled programs were removed. Recall from Chapter 4 that five programs were removed because they had a major overhaul in the program that resulted in a new MDS and new unit cost for that specific MDS. Our data relied on grouping the aircraft variants by time from IOC but we could not have programs in the model with two different unit costs for the same program.

Considerations for Further Research

- Explore smaller increments in bounds rather than using 5%, 10%, 15%, and 20%. This would involve exploring the best bound selection and going to smaller increments. For example, if the best bound was 15% then process could be done to explore 11%, 12%, 13, and 14% as thresholds.
- Use the same methodology for stability to investigate properties of other services or other types of programs. The VAMOSC database provides O&S data for other services and types of programs. For other services aircraft, comparisons in stability properties could be made with Air Force aircraft programs.
- Investigate why cost element 3 (CES 3) or WSER centralized asset management costs (WSER 1) do not exhibit stability properties. Could test a variety of programmatic variables provided by AFTOC to see why programs stabilize or not.
- In addition, investigate CES 4, 5, 6 for stability properties.
- Create a regression model to predict O&S costs for other services aircraft or programs using the available programmatic data provided by VAMOSC.

Chapter Summary

Programs that are in the sustainment phase face perpetual funding issues. If we are able to better predict when these costs stabilize, then it is easier to budget properly across all programs. Additionally, stability allows cost estimators to know when they can use actual costs for a basis of estimate methodology rather than using data from analogous programs.

This chapters first discusses the WSER and provides new threshold recommendations for reporting cost overruns. From there, it turns to the perspective of the cost estimator and helps discern when O&S costs can be considered stable with some degree of fidelity. Then an analysis of these stability properties is applied to different aircraft types to determine if there are any differences. While there are no inferential statistics due to sample size, there are evident trends that are expressed for different aircraft types. Assuming that the data is an actual representation of real programs for that specific type, this can also be helpful for cost estimators when trying to determine a stability point for O&S costs when working on a specific program. The aggregate level data coupled with the data for each aircraft type can help estimators and leaders in decision making.

The second part of Chapter 5 shows the results from the regression portion of analysis. We show that the multiple regression model does accurately predict the total O&S cost per TAI for aircraft with the help of certain predictor variables. While tempo and unit cost can be hard to determine accurately, the other predictor variables help provide for a robust model that is able to describe around 88% of the variance in the data researched.

Given the relatively recent emphasis on O&S costs, research for O&S estimating is still burgeoning. Research to help drive the field of O&S estimating forward has been happening but this is the first research on investigating stability properties for O&S cost. Cost estimators will now have added a set of tools to help determine when stability occurs and a top level cross check for O&S costs per aircraft.

Appendix A: Mean Percent Difference by Cost Type

Total O&S

Years from IOC	O&S Total	CES 1	CES 2	CES 3	CES 4	CES 5
1	1432.0%	1817.9%	5561.7%	822.2%	627.5%	49.7%
2	76.1%	89.1%	84.3%	99.4%	85.8%	241.4%
3	85.8%	390.5%	55.8%	131.8%	254.4%	1694.9%
4	30.0%	35.2%	19.7%	47.1%	1321.1%	188.4%
5	38.4%	21.3%	28.4%	27984.8%	55.4%	39.8%
6	13.5%	21.1%	31.2%	15.4%	75.9%	137.3%
7	12.2%	19.4%	17.1%	22.4%	230.7%	96.4%
8	16.3%	14.2%	28.8%	29.0%	73.3%	51.9%
9	12.7%	10.5%	23.2%	19.8%	127.2%	68.2%
10	12.1%	9.6%	13.3%	20.2%	203.9%	60.3%
11	21.0%	21.7%	33.1%	23.1%	125.1%	113.3%
12	7.8%	9.1%	10.2%	12.9%	22.2%	26.9%
13	14.6%	11.5%	6.3%	39.5%	42.7%	33.2%
14	7.0%	7.5%	12.1%	11.7%	196.7%	57.9%
15	8.6%	9.8%	18.8%	22.4%	146.3%	26.3%
16	10.6%	8.7%	10.5%	24.7%	307.9%	97.0%
17	7.1%	7.9%	13.6%	12.8%	60.5%	38.5%
18	7.7%	7.6%	13.8%	19.1%	92.1%	45.4%
19	4.7%	4.7%	9.2%	11.6%	57.0%	36.1%
20	7.3%	8.5%	8.8%	13.3%	75.0%	32.6%
21	8.6%	6.4%	12.5%	19.6%	93.3%	50.5%
22	9.3%	9.1%	13.2%	17.7%	103.6%	113.1%
23	6.2%	8.2%	10.9%	13.4%	43.8%	41.9%
24	7.9%	14.2%	10.8%	16.2%	132.6%	149.5%
25	9.4%	11.6%	9.4%	12.2%	26.4%	46.1%
26	7.7%	7.6%	13.1%	15.1%	30.7%	22.5%
27	7.9%	5.3%	14.0%	14.5%	57.4%	46.6%
28	10.8%	9.1%	12.5%	18.6%	22.2%	54.0%
29	12.4%	11.9%	18.4%	17.8%	33.3%	176.6%
30	12.6%	9.6%	14.2%	14.5%	42.7%	269.9%
31	9.0%	7.6%	13.0%	11.4%	52.7%	24.8%
32	11.1%	8.9%	18.4%	14.1%	45.9%	38.2%
33	16.7%	15.0%	18.5%	21.4%	30.1%	86.6%
34	16.0%	13.7%	18.3%	18.3%	50.6%	2809.0%
35	17.2%	19.1%	20.4%	21.4%	50.1%	95.0%
36	9.5%	6.1%	12.7%	16.7%	30.1%	69.0%
37	10.0%	10.8%	14.2%	20.6%	28.4%	46.6%
38	11.4%	15.7%	10.9%	21.4%	46.9%	188.5%
39	13.6%	10.4%	17.8%	18.6%	31.4%	77.5%
40	15.9%	14.8%	19.5%	22.1%	56.8%	185.5%

Cost Per Fly Hour (CPFH)

Years from IOC	CPFH Total	CPFH CES 1	CPFH CES 2	CPFH CES 3	CPFH CES 4	CPFH CES 5
1	649.4%	874.5%	2772.6%	142.4%	190.4%	61.3%
2	42.0%	36.3%	52.9%	76.0%	50.6%	107.5%
3	20.0%	93.9%	17.4%	49.2%	133.1%	1327.7%
4	13.5%	14.9%	14.5%	37.2%	374.2%	134.8%
5	18.1%	11.5%	16.8%	18954.7%	55.5%	40.1%
6	14.9%	21.1%	21.2%	20.5%	70.3%	121.6%
7	13.7%	18.7%	13.6%	21.2%	174.3%	87.3%
8	15.6%	20.0%	20.2%	21.9%	61.5%	46.3%
9	12.4%	9.0%	24.5%	19.8%	103.9%	61.5%
10	10.0%	11.9%	11.5%	19.0%	192.0%	52.5%
11	13.6%	12.8%	13.1%	23.9%	78.2%	103.8%
12	10.8%	10.6%	12.3%	16.3%	24.2%	28.4%
13	13.5%	13.4%	5.7%	39.3%	42.0%	36.4%
14	5.4%	8.4%	8.0%	13.1%	197.0%	54.7%
15	11.3%	11.9%	20.1%	24.6%	140.4%	28.1%
16	10.3%	6.8%	8.3%	25.1%	314.3%	92.2%
17	8.0%	10.1%	14.6%	16.4%	61.0%	41.0%
18	9.6%	9.4%	10.3%	21.1%	89.1%	49.3%
19	9.0%	6.9%	8.3%	17.2%	64.1%	38.0%
20	7.4%	9.5%	8.1%	16.1%	77.0%	32.5%
21	13.3%	12.8%	12.5%	23.9%	96.6%	64.0%
22	9.0%	11.1%	12.1%	18.2%	98.5%	101.7%
23	9.0%	11.9%	6.4%	18.4%	45.7%	41.1%
24	9.3%	18.9%	8.9%	17.7%	152.1%	150.1%
25	7.0%	13.7%	6.4%	8.8%	22.4%	45.2%
26	15.8%	18.5%	8.9%	21.4%	40.3%	24.0%
27	9.1%	12.2%	8.9%	15.4%	56.0%	43.2%
28	16.6%	23.0%	10.3%	12.0%	25.6%	58.0%
29	9.6%	17.5%	9.7%	21.4%	36.8%	175.5%
30	13.1%	14.7%	15.3%	18.3%	36.8%	223.4%
31	8.9%	10.7%	10.5%	14.2%	57.3%	23.5%
32	8.9%	12.5%	9.6%	15.0%	72.6%	37.8%
33	7.0%	12.0%	9.2%	13.0%	36.1%	95.2%
34	10.2%	16.0%	8.6%	13.8%	46.3%	4096.2%
35	17.9%	21.8%	7.8%	29.5%	51.9%	124.0%
36	5.9%	7.3%	5.0%	13.8%	23.9%	66.8%
37	6.8%	13.0%	11.3%	15.5%	32.9%	43.0%
38	9.2%	16.3%	7.2%	18.7%	46.4%	192.6%
39	11.8%	13.2%	7.3%	23.1%	46.3%	81.9%
40	9.0%	11.6%	11.4%	17.0%	53.5%	174.4%

Cost Per Total Aircraft in the Inventory (CPTAI)

Years from IOC	CPTAI Total	CPTAI CES 1	CPTAI CES 2	CPTAI CES 3	CPTAI CES 4	CPTAI CES 5
1	644.8%	847.3%	2704.0%	246.4%	232.7%	37.8%
2	27.0%	24.7%	43.3%	60.6%	51.1%	100.7%
3	39.2%	207.0%	25.7%	70.0%	144.9%	1360.0%
4	13.3%	15.6%	15.8%	35.4%	945.8%	157.0%
5	23.5%	11.1%	17.2%	21263.8%	53.0%	40.3%
6	6.3%	11.9%	25.7%	12.0%	68.7%	117.2%
7	10.0%	14.5%	14.7%	20.7%	232.8%	70.7%
8	11.0%	11.4%	21.8%	24.6%	71.0%	46.6%
9	11.0%	7.3%	25.2%	18.2%	112.6%	63.5%
10	8.7%	7.4%	11.4%	18.5%	201.9%	56.0%
11	9.6%	8.3%	16.1%	20.8%	91.0%	91.2%
12	6.6%	6.9%	10.9%	11.7%	21.0%	25.8%
13	12.5%	9.5%	6.3%	36.4%	43.3%	33.4%
14	7.4%	7.1%	11.6%	11.9%	198.0%	54.8%
15	8.4%	8.9%	17.8%	22.3%	145.1%	27.9%
16	10.6%	8.4%	10.5%	25.2%	310.3%	94.0%
17	7.2%	6.8%	12.8%	13.8%	58.0%	39.7%
18	9.1%	7.2%	14.0%	22.2%	90.9%	48.4%
19	5.1%	4.5%	8.8%	12.3%	58.5%	37.3%
20	6.4%	8.2%	9.2%	14.7%	73.7%	31.0%
21	10.5%	7.9%	13.2%	21.4%	93.7%	54.5%
22	8.8%	8.3%	13.3%	18.0%	102.0%	113.4%
23	6.4%	6.7%	11.2%	15.6%	45.3%	43.6%
24	8.4%	13.2%	10.1%	17.6%	133.0%	149.5%
25	7.4%	11.2%	9.1%	10.1%	24.2%	45.9%
26	9.3%	9.0%	10.1%	17.1%	33.3%	22.6%
27	6.1%	5.9%	13.0%	12.5%	57.3%	45.8%
28	8.8%	10.9%	6.6%	16.8%	16.5%	53.7%
29	6.4%	8.9%	13.1%	13.3%	29.3%	178.5%
30	9.0%	6.9%	12.4%	14.1%	40.6%	278.9%
31	5.4%	4.1%	9.7%	9.4%	51.8%	26.2%
32	6.5%	5.5%	15.2%	10.9%	54.6%	35.0%
33	8.0%	5.7%	9.9%	15.3%	29.6%	94.0%
34	10.7%	9.0%	18.8%	12.4%	42.1%	7010.8%
35	13.3%	12.9%	12.4%	26.9%	43.5%	94.6%
36	7.5%	4.3%	11.6%	15.9%	28.9%	69.9%
37	8.7%	7.4%	12.8%	20.8%	39.6%	45.5%
38	11.5%	10.7%	13.8%	18.2%	45.3%	228.1%
39	7.8%	10.9%	12.4%	15.6%	36.3%	85.0%
40	11.6%	9.5%	16.1%	17.5%	58.7%	188.4%

Weapon System Enterprise Review (WSER) Categories

Years from IOC	WSER 1	WSER 2	WSER 3	CPFH WSER 1	CPFH WSER 2	CPFH WSER 3	CPTAI WSER 1	CPTAI WSER 2	CPTAI WSER 3
1									
2	136.4%	117.9%	92.2%	76.4%	28.9%	37.6%	70.4%	38.3%	30.2%
3	116.1%	118.3%	158.0%	32.0%	39.3%	36.7%	53.2%	58.9%	67.1%
4	1975.6%	43.7%	83.1%	377.8%	19.9%	18.0%	1314.2%	20.6%	37.3%
5	490.4%	29.4%	44.0%	313.3%	19.9%	23.0%	366.5%	20.3%	26.2%
6	27.9%	27.7%	30.3%	24.2%	21.6%	18.5%	16.4%	18.0%	12.1%
7	26.1%	20.8%	20.9%	19.8%	19.4%	15.4%	21.1%	14.3%	11.1%
8	24.1%	27.6%	26.7%	18.3%	25.9%	23.5%	17.7%	17.7%	22.7%
9	31.0%	18.9%	18.7%	24.1%	11.9%	13.8%	27.2%	13.1%	12.8%
10	18.1%	14.9%	16.7%	12.8%	17.0%	9.1%	12.1%	11.5%	10.2%
11	23.3%	15.4%	18.7%	20.6%	13.8%	12.4%	20.7%	11.1%	14.0%
12	21.5%	13.2%	19.2%	25.8%	10.7%	11.7%	19.6%	7.6%	14.0%
13	41.8%	13.1%	13.3%	40.3%	13.2%	15.5%	35.9%	9.8%	12.6%
14	15.8%	13.2%	14.7%	12.9%	13.7%	16.6%	15.3%	12.2%	14.7%
15	16.8%	18.8%	11.7%	18.4%	19.6%	13.6%	17.2%	17.3%	10.4%
16	24.1%	12.3%	11.0%	22.3%	8.7%	8.1%	24.7%	12.0%	10.2%
17	19.7%	11.7%	8.8%	23.6%	14.3%	12.2%	21.2%	11.4%	9.0%
18	10.9%	12.1%	9.9%	9.5%	12.5%	9.1%	11.5%	11.6%	9.0%
19	14.0%	9.9%	14.2%	20.6%	10.5%	14.4%	16.1%	8.6%	13.7%
20	10.0%	8.4%	9.4%	13.5%	11.2%	12.0%	12.0%	7.8%	9.9%
21	16.9%	9.9%	11.5%	22.9%	16.8%	15.0%	19.5%	12.0%	13.6%
22	12.4%	11.7%	10.3%	12.2%	12.2%	11.3%	12.8%	12.1%	11.5%
23	14.5%	8.1%	10.8%	19.2%	13.6%	9.3%	16.9%	7.9%	8.6%
24	17.3%	15.2%	15.6%	16.7%	20.7%	15.8%	18.7%	15.4%	15.8%
25	12.6%	13.3%	11.2%	10.6%	15.2%	10.8%	10.3%	13.3%	10.9%
26	14.1%	11.9%	12.3%	19.4%	23.3%	13.6%	13.5%	12.0%	8.0%
27	16.9%	9.8%	15.9%	15.0%	13.4%	21.5%	14.8%	7.8%	18.6%
28	19.0%	12.6%	19.1%	13.4%	20.0%	32.4%	15.6%	10.1%	22.9%
29	17.7%	16.6%	17.8%	20.0%	14.5%	17.9%	12.3%	13.2%	14.4%
30	15.9%	12.4%	30.3%	16.0%	15.5%	27.8%	13.1%	8.1%	25.2%
31	13.5%	11.8%	16.0%	11.1%	10.5%	14.8%	10.0%	6.6%	10.8%
32	15.3%	14.6%	20.5%	13.9%	13.5%	13.4%	10.7%	5.6%	19.5%
33	19.4%	16.6%	22.9%	15.7%	13.7%	18.8%	17.3%	5.5%	14.4%
34	21.0%	19.3%	158.1%	16.0%	14.1%	351.9%	10.4%	11.6%	639.1%
35	24.8%	18.3%	33.5%	28.1%	22.1%	35.6%	25.2%	11.5%	25.6%
36	15.8%	11.8%	15.9%	9.4%	9.9%	8.6%	14.5%	10.1%	12.7%
37	19.1%	15.3%	50.6%	14.6%	13.0%	54.3%	19.1%	9.2%	50.6%
38	14.1%	15.2%	16.5%	13.2%	13.2%	18.3%	12.3%	9.2%	22.9%
39	21.6%	18.8%	20.6%	22.4%	13.1%	16.6%	16.0%	15.4%	13.0%
40	31.1%	22.6%	25.2%	23.6%	16.3%	20.3%	26.7%	17.3%	19.9%

Appendix B: Best Bound Selections by Aircraft Type

Bomber

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30
Total O&S	20%	Yes	0	0	100.00%
	15%	Yes	3	3	88.89%
	10%	Yes	3	6	77.78%
	5%	No	5	13	48.00%
Total CES 1	20%	Yes	0	0	100.00%
	15%	Yes	0	0	100.00%
	10%	Yes	0	2	93.33%
	5%	Yes	0	12	60.00%
Total CES 2	20%	Yes	1	2	93.10%
	15%	Yes	2	6	78.57%
	10%	Yes	2	14	50.00%
	5%	No	2	22	21.43%
Total CES 3	20%	Yes	1	5	82.76%
	15%	Yes	1	8	72.41%
	10%	Yes	1	13	55.17%
	5%	No	0	0	0.00%
CPFH Total	20%	Yes	2	3	89.29%
	15%	Yes	2	4	85.71%
	10%	Yes	2	13	53.57%
	5%	No	2	19	32.14%
CPFH CES 1	20%	Yes	0	6	80.00%
	15%	Yes	2	7	75.00%
	10%	Yes	3	12	55.56%
	5%	No	3	20	25.93%
CPFH CES 2	20%	Yes	2	1	96.43%
	15%	Yes	3	2	92.59%
	10%	No	24	5	16.67%
	5%	No	N/A		
CPFH CES 3	20%	Yes	3	4	85.19%
	15%	No	4	14	46.15%
	10%	No	N/A		
	5%	No	N/A		
CPTAI Total	20%	Yes	0	0	100.00%
	15%	Yes	0	4	86.67%
	10%	Yes	0	9	70.00%
	5%	Yes	5	12	52.00%
CPTAI CES 1	20%	Yes	0	0	100.00%
	15%	Yes	0	0	100.00%
	10%	Yes	0	4	86.67%
	5%	Yes	3	9	66.67%
CPTAI CES 2	20%	Yes	1	2	93.10%
	15%	Yes	1	7	75.86%
	10%	Yes	2	14	50.00%
	5%	No	2	21	25.00%
CPTAI3 %1	20%	Yes	0	5	83.33%
	15%	Yes	0	10	66.67%
	10%	No	1	15	48.28%
	5%	No	N/A		

Fighter/Attack

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30	# Outside Bound (37)	% Stable to 37
Total O&S	20%	Yes	3	0	100.00%	3	91.18%
	15%	Yes	4	1	96.15%	6	81.82%
	10%	Yes	6	4	83.33%	11	64.52%
	5%	No	6	20	16.67%	27	12.90%
Total CES 1	20%	Yes	4	1	96.15%	4	87.88%
	15%	Yes	4	1	96.15%	4	87.88%
	10%	Yes	6	5	79.17%	9	70.97%
	5%	No	8	13	40.91%	19	34.48%
Total CES 2	20%	Yes	3	1	96.30%	4	88.24%
	15%	Yes	3	5	81.48%	9	73.53%
	10%	Yes	7	10	56.52%	15	50.00%
	5%	No	7	17	26.09%	24	20.00%
Total CES 3	20%	Yes	3	7	74.07%	12	64.71%
	15%	Yes	3	12	55.56%	18	47.06%
	10%	No	3	20	25.93%	27	20.59%
	5%	No	N/A				
CPFH Total	20%	Yes	2	4	85.71%	5	85.71%
	15%	Yes	2	5	82.14%	6	82.86%
	10%	Yes	2	9	67.86%	11	68.57%
	5%	No	4	21	19.23%	27	18.18%
CPFH CES 1	20%	Yes	0	6	80.00%	7	81.08%
	15%	Yes	0	9	70.00%	11	70.27%
	10%	Yes	0	13	56.67%	17	54.05%
	5%	No	9	15	28.57%	20	28.57%
CPFH CES 2	20%	Yes	2	0	100.00%	0	100.00%
	15%	Yes	2	2	92.86%	2	94.29%
	10%	Yes	2	6	78.57%	7	80.00%
	5%	No	9	16	23.81%	21	25.00%
CPFH CES 3	20%	Yes	2	9	67.86%	11	68.57%
	15%	No	3	14	48.15%	17	50.00%
	10%	No	N/A				
	5%	No	N/A				
CPTAI Total	20%	Yes	2	0	100.00%	1	97.14%
	15%	Yes	2	0	100.00%	1	97.14%
	10%	Yes	2	5	82.14%	10	71.43%
	5%	No	2	23	17.86%	30	14.29%
CPTAI CES 1	20%	Yes	2	1	96.43%	0	100.00%
	15%	Yes	3	2	92.59%	0	100.00%
	10%	Yes	3	7	74.07%	8	76.47%
	5%	No	4	15	42.31%	20	39.39%
CPTAI CES 2	20%	Yes	0	1	96.67%	2	94.59%
	15%	Yes	0	2	93.33%	3	91.89%
	10%	Yes	0	8	73.33%	12	67.57%
	5%	No	1	22	24.14%	29	19.44%
CPTAI3 %1	20%	Yes	1	7	75.86%	11	69.44%
	15%	Yes	1	12	58.62%	16	55.56%
	10%	No	3	18	33.33%	24	29.41%
	5%	No	N/A				

Helicopters

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30	# Outside Bound (40)	% Stable to 40
Total O&S	20%	Yes	10	3	85.00%	4	86.67%
	15%	Yes	10	3	85.00%	4	86.67%
	10%	Yes	10	8	60.00%	10	66.67%
	5%	No	10	14	30.00%	20	33.33%
Total CES 1	20%	Yes	10	2	90.00%	4	86.67%
	15%	Yes	10	3	85.00%	6	80.00%
	10%	Yes	10	5	75.00%	9	70.00%
	5%	No	10	11	45.00%	17	43.33%
Total CES 2	20%	Yes	10	6	70.00%	12	60.00%
	15%	Yes	10	7	65.00%	13	56.67%
	10%	No	10	11	45.00%	17	43.33%
	5%	No	N/A				
Total CES 3	20%	Yes	10	5	75.00%	7	76.67%
	15%	No	10	11	45.00%	13	56.67%
	10%	No	N/A				
	5%	No	N/A				
CPFH Total	20%	Yes	10	2	90.00%	3	90.00%
	15%	Yes	10	3	85.00%	6	80.00%
	10%	Yes	10	5	75.00%	9	70.00%
	5%	No	10	13	35.00%	18	40.00%
CPFH CES 1	20%	Yes	10	1	95.00%	4	86.67%
	15%	Yes	10	3	85.00%	7	76.67%
	10%	Yes	10	6	70.00%	11	63.33%
	5%	No	10	13	35.00%	19	36.67%
CPFH CES 2	20%	Yes	10	4	80.00%	11	63.33%
	15%	Yes	10	8	60.00%	15	50.00%
	10%	No	10	15	25.00%	22	26.67%
	5%	No	N/A				
CPFH CES 3	20%	Yes	10	8	60.00%	10	66.67%
	15%	Yes	10	10	50.00%	12	60.00%
	10%	No	10	12	40.00%	19	36.67%
	5%	No	N/A				
CPTAI Total	20%	Yes	10	3	85.00%	4	86.67%
	15%	Yes	10	3	85.00%	6	80.00%
	10%	Yes	10	6	70.00%	9	70.00%
	5%	No	10	16	20.00%	23	23.33%
CPTAI CES 1	20%	Yes	10	1	95.00%	3	90.00%
	15%	Yes	10	4	80.00%	8	73.33%
	10%	Yes	10	6	70.00%	11	63.33%
	5%	No	10	13	35.00%	20	33.33%
CPTAI CES 2	20%	Yes	10	5	75.00%	11	63.33%
	15%	Yes	10	6	70.00%	13	56.67%
	10%	No	10	12	40.00%	19	36.67%
	5%	No	N/A				
CPTAI CES 3	20%	Yes	10	6	70.00%	8	73.33%
	15%	No	10	11	45.00%	14	53.33%
	10%	No	N/A				
	5%	No	N/A				

Reconnaissance

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30	# Outside Bound (39)	% Stable to 39
Total O&S	20%	Yes	1	5	82.76%	6	84.21%
	15%	Yes	1	8	72.41%	10	73.68%
	10%	Yes	6	5	79.17%	7	78.79%
	5%	Yes	12	9	50.00%	14	48.15%
Total CES 1	20%	Yes	2	1	96.43%	1	97.30%
	15%	Yes	4	1	96.15%	2	94.29%
	10%	Yes	8	2	90.91%	4	87.10%
	5%	Yes	8	9	59.09%	14	54.84%
Total CES 2	20%	Yes	3	8	70.37%	10	72.22%
	15%	Yes	10	4	80.00%	7	75.86%
	10%	Yes	10	8	60.00%	11	62.07%
	5%	No	10	14	30.00%	20	31.03%
Total CES 3	20%	Yes	1	10	65.52%	12	68.42%
	15%	Yes	1	12	58.62%	16	57.89%
	10%	No	5	16	36.00%	21	38.24%
	5%	No	N/A				
CPFH Total	20%	Yes	3	4	85.19%	5	86.11%
	15%	Yes	3	6	77.78%	8	77.78%
	10%	Yes	3	12	55.56%	15	58.33%
	5%	No	6	20	16.67%	26	21.21%
CPFH CES 1	20%	Yes	3	3	88.89%	5	86.11%
	15%	Yes	4	3	88.46%	7	80.00%
	10%	No	5	15	40.00%	21	38.24%
	5%	No	N/A				
CPFH CES 2	20%	Yes	2	4	85.71%	4	89.19%
	15%	Yes	2	5	82.14%	5	86.49%
	10%	Yes	3	12	55.56%	12	66.67%
	5%	No	3	21	22.22%	25	30.56%
CPFH CES 3	20%	Yes	1	6	79.31%	8	78.95%
	15%	Yes	4	9	65.38%	13	62.86%
	10%	No	4	18	30.77%	22	37.14%
	5%	No	N/A				
CPTAI Total	20%	Yes	2	2	92.86%	2	94.59%
	15%	Yes	3	3	88.89%	4	88.89%
	10%	Yes	6	5	79.17%	7	78.79%
	5%	No	6	14	41.67%	19	42.42%
CPTAI CES 1	20%	Yes	5	0	100.00%	0	100.00%
	15%	Yes	5	1	96.00%	1	97.06%
	10%	Yes	5	4	84.00%	4	88.24%
	5%	Yes	10	7	65.00%	9	68.97%
CPTAI CES 2	20%	Yes	2	7	75.00%	9	75.68%
	15%	Yes	2	9	67.86%	13	64.86%
	10%	No	2	16	42.86%	21	43.24%
	5%	No	N/A				
CPTAI CES 3	20%	Yes	2	7	75.00%	10	72.97%
	15%	Yes	3	9	66.67%	13	63.89%
	10%	No	3	14	48.15%	21	41.67%
	5%	No	N/A				

Special Duty

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30
Total O&S	20%	Yes	3	4	85.19%
	15%	Yes	3	5	81.48%
	10%	Yes	4	11	57.69%
	5%	No	5	21	16.00%
Total CES 1	20%	Yes	1	4	86.21%
	15%	Yes	1	4	86.21%
	10%	Yes	1	10	65.52%
	5%	No	1	21	27.59%
Total CES 2	20%	Yes	3	7	74.07%
	15%	Yes	3	13	51.85%
	10%	No	3	20	25.93%
	5%	No	N/A		
Total CES 3	20%	Yes	2	13	53.57%
	15%	No	8	12	45.45%
	10%	No	N/A		
	5%	No	N/A		
CPFH Total	20%	Yes	1	5	82.76%
	15%	Yes	1	10	65.52%
	10%	No	2	17	39.29%
	5%	No	N/A		
CPFH CES 1	20%	Yes	1	6	79.31%
	15%	Yes	1	11	62.07%
	10%	No	1	18	37.93%
	5%	No	N/A		
CPFH CES 2	20%	Yes	3	8	70.37%
	15%	Yes	3	11	59.26%
	10%	No	3	18	33.33%
	5%	No	N/A		
CPFH CES 3	20%	Yes	2	13	53.57%
	15%	No	4	19	26.92%
	10%	No	N/A		
	5%	No	N/A		
CPTAI Total	20%	Yes	0	3	90.00%
	15%	Yes	0	7	76.67%
	10%	Yes	4	11	57.69%
	5%	No	5	20	20.00%
CPTAI CES 1	20%	Yes	0	2	93.33%
	15%	Yes	0	3	90.00%
	10%	Yes	3	10	62.96%
	5%	No	3	18	33.33%
CPTAI CES 2	20%	Yes	0	8	73.33%
	15%	Yes	0	12	60.00%
	10%	No	3	19	29.63%
	5%	No	N/A		
CPTAI CES 3	20%	Yes	0	15	50.00%
	15%	No	0	19	36.67%
	10%	No	N/A		
	5%	No	N/A		

Training

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (24)	% Stable to 24
Total O&S	20%	Yes	5	2	89.47%
	15%	Yes	6	2	88.89%
	10%	Yes	8	2	87.50%
	5%	No	9	9	40.00%
Total CES 1	20%	Yes	8	3	81.25%
	15%	Yes	8	3	81.25%
	10%	Yes	9	3	80.00%
	5%	No	12	8	33.33%
Total CES 2	20%	Yes	4	1	95.00%
	15%	Yes	6	3	83.33%
	10%	Yes	6	5	72.22%
	5%	No	8	12	25.00%
Total CES 3	20%	Yes	2	7	68.18%
	15%	No	5	10	47.37%
	10%	No	N/A		
	5%	No	N/A		
CPFH Total	20%	Yes	1	1	95.65%
	15%	Yes	1	3	86.96%
	10%	Yes	2	6	72.73%
	5%	No	3	14	33.33%
CPFH CES 1	20%	Yes	1	5	78.26%
	15%	Yes	1	6	73.91%
	10%	Yes	2	7	68.18%
	5%	No	2	17	22.73%
CPFH CES 2	20%	Yes	2	1	95.45%
	15%	Yes	2	3	86.36%
	10%	Yes	2	6	72.73%
	5%	No	3	14	33.33%
CPFH CES 3	20%	Yes	1	8	65.22%
	15%	Yes	1	11	52.17%
	10%	No	8	11	31.25%
	5%	No	N/A		
CPTAI Total	20%	Yes	0	1	95.83%
	15%	Yes	0	2	91.67%
	10%	Yes	1	4	82.61%
	5%	No	2	14	36.36%
CPTAI CES 1	20%	Yes	0	5	79.17%
	15%	Yes	0	6	75.00%
	10%	Yes	0	7	70.83%
	5%	No	4	15	25.00%
CPTAI CES 2	20%	Yes	1	2	91.30%
	15%	Yes	2	4	81.82%
	10%	Yes	2	6	72.73%
	5%	No	2	18	18.18%
CPTAI CES 3	20%	Yes	0	7	70.83%
	15%	Yes	0	11	54.17%
	10%	No	0	17	29.17%
	5%	No	N/A		

Transport/Tanker

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (30)	% Stable to 30	# Outside Bound (40)	% Stable to 40
Total O&S	20%	Yes	6	4	83.3%	5	85.3%
	15%	Yes	11	1	94.7%	3	89.7%
	10%	Yes	11	4	78.9%	10	65.5%
	5%	No	18	9	25.0%	19	13.6%
Total CES 1	20%	Yes	4	6	76.9%	6	83.3%
	15%	Yes	4	9	65.4%	10	72.2%
	10%	Yes	13	7	58.8%	11	59.3%
	5%	No	16	12	14.3%	21	12.5%
Total CES 2	20%	Yes	2	6	78.6%	9	76.3%
	15%	Yes	8	5	77.3%	10	68.8%
	10%	Yes	11	9	52.6%	19	34.5%
	5%	No	11	17	10.5%	27	6.9%
Total CES 3	20%	Yes	5	6	76.0%	9	74.3%
	15%	Yes	6	9	62.5%	12	64.7%
	10%	No	11	13	31.6%	20	31.0%
	5%	No	N/A				
CPFH Total	20%	Yes	2	1	96.4%	1	97.4%
	15%	Yes	2	1	96.4%	1	97.4%
	10%	Yes	4	8	69.2%	10	72.2%
	5%	No	4	22	15.4%	31	13.9%
CPFH CES 1	20%	Yes	1	2	93.1%	3	92.3%
	15%	Yes	2	8	71.4%	12	68.4%
	10%	No	2	18	35.7%	26	31.6%
	5%	No	N/A				
CPFH CES 2	20%	Yes	2	1	96.4%	1	97.4%
	15%	Yes	2	2	92.9%	2	94.7%
	10%	Yes	2	12	57.1%	14	63.2%
	5%	No	2	21	25.0%	28	26.3%
CPFH CES 3	20%	Yes	6	7	70.8%	10	70.6%
	15%	Yes	9	10	52.4%	15	51.6%
	10%	No	11	13	31.6%	21	27.6%
	5%	No	N/A				
CPTAI Total	20%	Yes	1	1	96.6%	1	97.4%
	15%	Yes	1	1	96.6%	1	97.4%
	10%	Yes	5	4	84.0%	5	85.7%
	5%	No	7	14	39.1%	22	33.3%
CPTAI CES 1	20%	Yes	1	1	96.6%	0	100.0%
	15%	Yes	1	2	93.1%	3	92.3%
	10%	Yes	1	7	75.9%	9	76.9%
	5%	No	3	18	33.3%	22	40.5%
CPTAI CES 2	20%	Yes	1	4	86.2%	5	87.2%
	15%	Yes	1	7	75.9%	9	76.9%
	10%	No	1	18	37.9%	23	41.0%
	5%	No	N/A				
CPTAI CES 3	20%	Yes	5	8	68.0%	8	77.1%
	15%	Yes	5	11	56.0%	15	57.1%
	10%	No	9	13	38.1%	20	35.5%
	5%	No	N/A				

Unmanned Aerial Vehicles (UAV)

Cost	Bound	50% Stability Reached?	Years to Reach Bound	# Outside Bound (11)	% Stable to 11
Total O&S	20%	Yes	5	2	66.67%
	15%	No	5	4	33.33%
	10%	No	N/A		
	5%	No	N/A		
Total CES 1	20%	Yes	5	3	50.00%
	15%	No	5	4	33.33%
	10%	No	N/A		
	5%	No	N/A		
Total CES 2	20%	No	3	5	37.50%
	15%	No	N/A		
	10%	No	N/A		
	5%	No	N/A		
Total CES 3	20%	Yes	5	2	66.67%
	15%	Yes	8	1	66.67%
	10%	Yes	9	1	50.00%
	5%	No	0	0	0.00%
CPFH Total	20%	Yes	5	1	83.33%
	15%	Yes	5	1	83.33%
	10%	Yes	8	0	100.00%
	5%	No	0	0	0.00%
CPFH CES 1	20%	Yes	4	2	71.43%
	15%	Yes	8	1	66.67%
	10%	Yes	8	1	66.67%
	5%	No	0	0	0.00%
CPFH CES 2	20%	Yes	6	2	60.00%
	15%	Yes	9	1	50.00%
	10%	No	0	0	0.00%
	5%	No	N/A		
CPFH CES 3	20%	Yes	5	1	83.33%
	15%	Yes	5	1	83.33%
	10%	Yes	7	1	75.00%
	5%	No	0	0	0.00%
CPTAI Total	20%	Yes	5	1	83.33%
	15%	Yes	5	1	83.33%
	10%	Yes	5	3	50.00%
	5%	No	0	0	0.00%
CPTAI CES 1	20%	Yes	4	2	71.43%
	15%	Yes	5	3	50.00%
	10%	No	6	4	20.00%
	5%	No	N/A		
CPTAI CES 2	20%	Yes	6	2	60.00%
	15%	No	0	0	0.00%
	10%	No	N/A		
	5%	No	N/A		
CPTAI3 %1	20%	Yes	5	1	83.33%
	15%	Yes	5	1	83.33%
	10%	Yes	9	1	50.00%
	5%	No	0	0	0.00%

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Vita

First Lieutenant Scott C. Hewitson graduated from Cherry Creek High School in Greenwood Village, Colorado. He entered undergraduate studies at the United States Air Force Academy, Colorado where he graduated with a Bachelor of Science degree in Business Management. Following the completion of his undergraduate degree, he was commissioned as an Officer in the United States Air Force.

His first assignment was at Wright-Patterson AFB as a budget analyst in the Human Systems Division program office. In August of 2016, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology. Upon graduation, he will be assigned to the Air Force Cost Analysis Agency at Joint Base Andrews in Maryland.

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14. ABSTRACT

Accurately predicting Operating and Support (O&S) costs is vital in the current climate of budgetary constraints. However, there is an overall lack of research in the realm of O&S which hinders cost estimator's abilities to provide accurate sustainment estimates. This research determines when Air Force Aircraft O&S costs stabilize and to what degree. Stability is examined in three areas: total O&S costs, the six O&S cost element structures, and aircraft type. Stability results vary by category but generally is found to occur 80% of the time at approximately five years from Initial Operating Capability (IOC). The second portion of this research employs a multiple regression model to predict median O&S costs per total active aircraft in the inventory (CPTAI). All O&S costs and variables for regression derived from the literature are collected using the Air Force Total Ownership Cost (AFTOC) database. The model explains 87.24% of the variance in the data set when predicting median O&S CPTAI. Results from this research provide insight to cost estimators on when to start using actual O&S costs as a baseline for estimates in lieu of analogous programs and provides a new parametric O&S estimating tool designed as a cross-check to current estimating methodologies.

15. SUBJECT TERMS

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